Sustainable Historic Environments holistic reconstruction through Technological Enhancement & community-based Resilience

D 3.4 Adaptation and reconstruction portfolio to improve CH buildings and sites resilience

Version number	1.0
Dissemination level	PU
Lead partner	NOBATEK
Due date	31.05.2021
Type of deliverable	other
Status	delivered

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821282

Published in the framework of:

SHELTER - Sustainable Historic Environments hoListic reconstruction through Technological Enhancement & community-based Resilience

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Revision and history chart:

VERSION	DATE	AUTHOR/EDITOR	COMMENT
0.1	06/04/2021	NBK	TOC
0.2	29/04/2021	NBK, EKO, UMAS, UPV/EHU	First draft. Authors have provided contributions.
0.3	18/05/2021	NBK	NBK collects all the comments from reviewers and update the D3.4
0.5	20/05/2021	UPV/EHU, EKO	UPV, EKO, IHED, LINKS, provide the final comments
1.0	25/05/2021	NBK	NBK provides the final version according to comments

Disclaimer:

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Glossary

Acronym	Full name
AS	Adaptative Solution
BBB	Building Back Better
CBA	Cost Benefit Analysis
CCA	Climate Change Adaptation
CH	Cultural Heritage
CHM	Cultural Heritage Management
CNH	Cultural and Natural Heritage
DRM	Disaster Risk Management
DSS	Decision Support System
EoL	End-of-life
HA	Historic Area
LCA	Life Cycle Assessment
LCT	Life Cycle Thinking
LCC	Life Cycle Costing
NBS	Nature Based Solutions
OL	Open Lab
PI	Prioritization Index
S-LCA	Social life cycle assessment
UHI	Urban Heat Island
WP	Work Package

1 Executive summary

The purpose of this deliverable D3.4 is to provide a solutions and strategies portfolio together with a prioritization tool for decision making, and a tool for cost-benefit analysis.

As a first step, solutions characterization sheets have been defined and completed in a collaborative way between task partners as well as Open Labs stakeholders. The characterization sheets also include the Life Cycle Assessment (LCA) for each solution. Afterwards, to provide strong support to the end-user a prioritization tool has been developed by the project team based on the core data of the portfolio and a set criterion previously defined. It has also been developed a Cost-Benefit Analysis (CBA) tool which allows a better understanding of the solutions/strategy's impacts, but also to better lead the user into his or her decision.

The Portfolio allows gathering all the characteristics of the identified solutions and strategies which match Climate Change Adaptation (CCA) and Disaster Risk Management (DRM). The completed work allows moving forward into the support of CCA and DRM solutions and strategies.

The developed tools (Portfolio, prioritization tool, LCA and CBA) will be implemented in the Decision Support System (DSS) and will be spread to Open Labs (OL). Indeed, the tool will be shared and use, first by Open Labs and later will be shared with more end-users.

The Portfolio includes solutions and strategies related to the different DRM phases: Prevention, Preparedness, Response and Recovery. Solutions and strategies are also addressing different hazard typologies such as flood, earthquake, storm, subsidence, wildfire and heatwaves. They are also specified by typology, focusing on Nature-Based Solution (NBS), vernacular solutions and circular economy. All this work has been conducted in close link with task 3.3 which included solutions for the emergency phases.

The Portfolio (including the prioritization index), the LCA tool (included in the portfolio) and the CBA tool are provided at the following link: D3.4 Tools

2 Introduction

Over the last decades, as a consequence of the effects of climate change, Cultural and Natural Heritage (CNH) has been impacted by an increasing number of climate-related hazards, posing new challenges to conservators and heritage managers. SHELTER aims at developing a data-driven and community-based knowledge framework that will bring together the scientific community and heritage managers with the objective of increasing resilience, reducing vulnerability and promoting better and safer reconstruction maintenance in historic areas.

Climate-related risks to Historic Areas (HA) are dependent on the nature of the hazard, specific characteristics of the exposed elements, as well as the inherent vulnerability and geographical environment of the HA site. Because of climate change, catastrophic events are increasing in frequency and intensity, leading to an increase in CNH losses. Conservation interventions in HA sites generally focus on the long-term deterioration of the site materials and the works of art. However, conservation interventions are rarely focusing on emergency management phases and sudden damages, that's why the Portfolio included this phase. Nevertheless, a large room has been provided for the other phases of the DRM. This deliverable contributes to this gap as part of the portfolio of solutions that SHELTER is compiling. These solutions focus on the hazards with more impact in CNH and have been proposed or went from five Open Labs (OL) that cover earthquakes, storms, floods, heat waves, wildfire and subsidence.

This deliverable is part of the work package (WP) 3, which aims at characterizing and developing cost-effective low carbon technological solutions to manage climate-related risks on the five Open Labs of the SHELTER project. In this specific case, the portfolio lists solutions and strategies for prevention, preparedness, response, and recovery to build back better (BBB). The portfolio, which includes a prioritization tool and a CBA tool, has been first built into an Excel sheet and will then give input to the SHELTER data-driven platform and its decision support system (DSS).

2.1 Aims and objectives

The purpose of this deliverable D3.4 is to support the end-users (professionals working or interested in DRM solutions for CNH, urban and heritage managers) to interpret the results of the solution data sheets (Portfolio). Therefore, the report targets two audiences: i) technical readers who are interested in the development and implementation of solutions and strategies and selection tool and ii) end-users of the Portfolio who can be heritage managers (private organisation, association, municipality…). The deliverable provides an understanding of the completed work but also provide a breakdown of the completed action which has led to the final Excel Portfolio.

Task 3.4 is itself divided into three sub-tasks:

- **ST 3.4.1** for the identification and the characterisation of solutions and strategies for adaptation and Building Back Better. Solutions are defined as technical actions which request the implementation of a clear and already define knowledge to tackle the target issue. Whereas, strategies are defined as a sum of actions that are not technical and non-exhaustive which can lead to tackle or mitigate the targeted impact on heritage. All solutions are assessed with a preliminary qualitative Life Cycle Assessment (LCA) about the environmental impact of the materials employed for their implementation. End-users can carry out a more detailed LCA for selected solutions regarding spatial interventions impact, construction impact and other material flows to ensure their low carbon characteristics. Local knowledge (professionals) has been also considered, through Open Labs (WP7), to identify and evaluate the best solutions for specific local contexts. Open Labs gather professionals and qualified persons working in disaster risk and cultural heritage management.

- **ST 3.4.2** the development of the Cost-Benefit Analysis (CBA) of solutions, has been completed. Qualitative and quantitative assessment of the systems, technologies and eco-innovative solutions has been performed by looking at benefits (monetary and non-monetary) and running an in-depth CBA, quantifying the main benefits, costs and investments required for each of them.
- **ST 3.4.3** builds the portfolio of existing solutions and strategies for adaptation and Building Back Better. By means of a prioritisation tool, end-users can compare the selected solution in relation to technical, socio-economic and environmental criteria like implementation cost (including a high-level assessment of costs and investments), ease of implementation, duration of the works, resources required, regulatory framework, added value and impact of the solution, LCA or capacity to boost the local economy. The T3.4 actions have been linked to Best/Next Practices Observatory and updated with the results of Open Labs.

2.2 Relations to other activities in the project

SHELTER project has been structured in 9 work packages to ensure cross-fertilization among the different steps and partners. One of the objectives of WP3 is to characterize and develop cost-effective low carbon technological solutions for prevention, preparedness, response and recovery through building back better and integrate them in a dynamic portfolio to be used for the data-driven platform in strategic DSS (WP5). WP3 is also closely related to the WP2 (Knowledge generation: Systemic Historic Area resilience assessment and monitoring) which purpose is to produce a knowledge generation methodology to build multidimensional, cross-scale and systemic resilience assessment and monitoring workflows that will provide information in all the phases of DRM (see Figure 1):

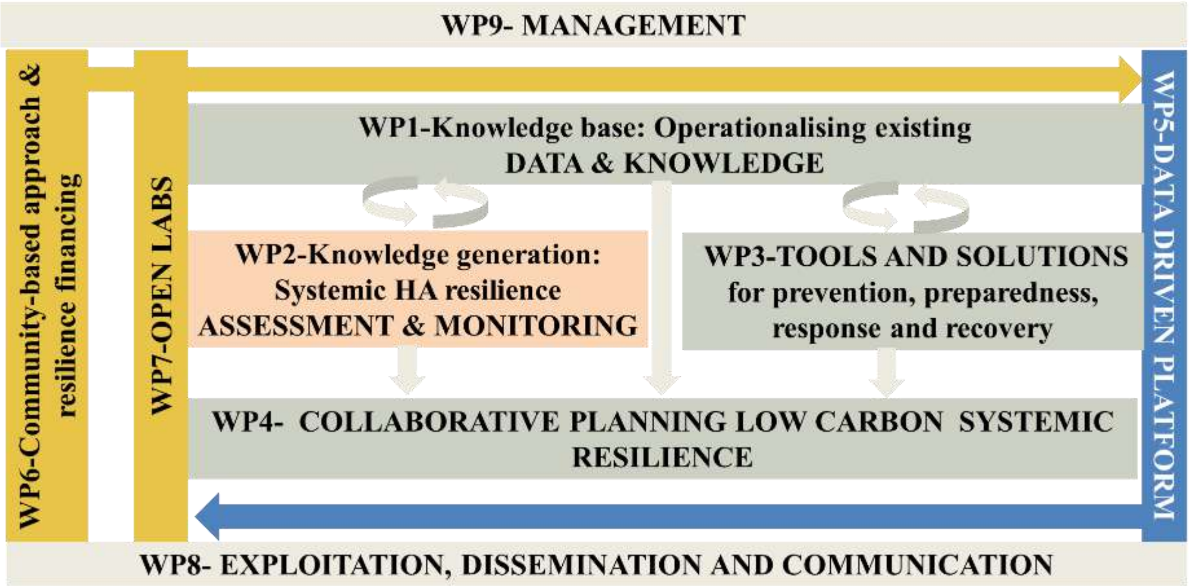


Figure 1 PERT chart of SHELTER

WP3 (Tools and solutions for prevention, preparedness, response and recovery) seeks to characterize and develop cost-effective low carbon technological solutions for prevention, preparedness, response and recovery through building back better (BBB) and integrate them in a dynamic portfolio to be used for the data-driven platform in Strategic DSS (WP5).

Apart from the direct relation with Task 3.3, Task 3.4 regarding the development of a solution/strategy portfolio and prioritization tool was linked with other WPs of the SHELTER project. The main relationships were the following:

- **WP2** (Knowledge generation: Systemic Historic Area resilience assessment and monitoring). Especially linked with T2.2 for the systemic resilience assessment and monitoring framework for HA: structure of indicators, the definition of KPIs and resilience co-monitoring strategy and the T2.3 about Climate Hazard categorization. Solutions aiming at reducing risk (T2.5) and improving the resilience of historic areas and assets (T2.7), and CNH characterization (T2.3) have been included in the Portfolio into the T3.4
- **WP5** (Data-Driven Platform), the indicators developed in the hereby described task will support the diagnosis, decision making and monitoring methodologies that will be supported in the platform. The portfolio developed into the T3.4 will be implemented into a decision support system developed into the WP5
- In **WP7,** Open Labs are functioning as knowledge generator and evaluation frameworks, demonstration sites, long-term thinking transition labs and learning environments. Task 3.4 has worked closely with OLs to define the local solutions or strategies suitable to be implemented into the portfolio.

2.3 Report structure

The D3.4 presents the methodology through which the portfolio, the prioritization tool but also the LCA and CBA tools have been developed. The portfolio is the compilation of the characterisation sheets of solutions and strategies which can help heritage manager to mitigate the impact of climate hazards. The portfolio, described in section 3, takes into account the different DRM phases, the different hazard and the solution typology. The T3.4 has developed the portfolio under an Excel spreadsheet. This Portfolio includes the Prioritisation tool, presented in section 3. Belonging this unique portfolio come two tools the LCA and the CBA. The LCA tool has been included in the portfolio while the CBA is a separate tool. The D3.4 presents the portfolio, the prioritization tool and the related LCA and CBA tools under the following sections:

Section 1 presents the executive summary of the deliverable,
Section 2 summarises the content of the deliverables with aims, objectives and the partner contributions,
Section 3 describes the development of the solutions and strategies portfolio. The construction of the data-sheet template is explained, the filling process and the prioritization tool as well.
Section 4 presents the methodology of development and implementation of the Life Cycle Assessment tool. The section also explains the use of the LCA
Section 5 explains the methodology of development and implementation of the Cost-Benefit Analysis tool
Section 6 summarises the conclusions and next steps

2.4 Contribution of partners

NBK, as coordinator of the T3.4, has managed the construction of the Portfolio with the support of contributors such as WP3 partners, WP5 partners and Open Labs in WP7. In the related deliverable here D3.4, NBK has participated in the definition of the Table of Content, the definition of the portfolio methodology. NBK has also participated in the construction of the portfolio establishing the date sheets for Nature-Based Solutions, storm and subsidence.

EKO, as responsible for the Life Cycle Assessment aspect proposed a simplified methodology for its implementation in this portfolio of solutions. EKO has also provided the description of the construction, development and implementation of the simplified LCA to the characterisation sheets included in the Portfolio. EKO has also participated in the construction of the portfolio establishing the datasheets for Vernacular Architecture and earthquakes.

UMAS, as responsible for the CBA (Cost-Benefit analysis), has provided a simplified and replicable methodology. This methodology has been developed in collaboration with EKO and the T3.4 partners. UMAS provided a description of the methodology construction and of its implantation to case studies present in the Portfolio.

TEC has participated in the completion of the details of characterisation sheets for Circular Economy and flooding.

UPV/EHU has participated in the definition of the methodology used in T3.4.1, has facilitated a proposal solution data sheet (based on the template used in T3.3), has developed the prioritization methodology and has also participated in the completion of the details of sheets for emergency solutions for structural stabilization and consolidation, heat waves and wildfires.

3 Development of the solutions and strategies portfolio

The portfolio proposes a set of solutions and strategies characterisation sheets for different DRM phases and hazards, and focusing on these fields: Nature-Based Solutions (NBS), vernacular architecture, circular economy, solutions for structural consolidation and stabilization in an emergency (input from T3.3), and specific solutions for each DRM phase. Solutions and strategies are also addressing different hazard typologies such as flood, earthquake, storm, subsidence, wildfire and heatwaves. They are also specified by typology: Nature-Based Solution (NBS), vernacular solutions and circular economy. All this work has been conducted in close link with task T3.3 which included solutions for the emergency phases. Indeed, the T3.4 is not focused on the emergency phase but address the whole DRM phases. Thus, the collaborative work with the T3.3 allows providing a broad set of solutions and strategies for the different phase.

A prioritization tool has been developed to support the end-users decision. Indeed, the tool is targeted to Cultural Heritage (Building, urban and territory) owners/managers for their management and preservation actions against climate hazard.

Each characterisation sheet of the portfolio aims to present in a clear and as complete as possible way the solution/strategy that the end-user might select. The selection can be done according to criteria detailed in the characterization sheet (see figure 2 in section 3.1 below) as climate hazard, DRM phase, range of action, a protected element they are facing, protected and affected elements, technical description, economic and environmental information, advantages and inconveniences. The portfolio includes the tailor-made LCA tool which is implemented. Also, the CBA tool is an independent tool that allows providing a Cost-Benefit Analysis of the solutions and strategies for a better understanding and selection of the solutions by the end-users.

The portfolio and the prioritisation tool will be integrated into the Decision Support System (DSS) developed in WP5 to allow the end-users to filter the solutions and strategies according to their local context and so to extract the more relevant solutions or strategies for their sites.

3.1 The methodology for the data collection of listed solutions

Task partners adapted the solution characterization data-sheet template facilitated by T3.3 to be applicable for all DRM phases and strategies. The methodology of construction of the template and of the data collection itself have been conducted in collaboration with Open Labs (OLs). The main purpose of the characterization sheets is to provide understandable, clear and complete information to the user. It includes technical, socio-economic, environmental and cultural information together with some general description, LCA information, pictures and references.

Collection of data was allocated to the partners of the task in function of identified technical fields (Circular Economy, Nature-Based Solutions (NBS), Vernacular Architecture, Consolidation of Structure and Envelope in case of emergency (T3.3)) and expertise of partners. This work breakdown has been justified by the need to provide expert insight on the solutions/strategies which will be proposed into the portfolio. A transversal field was also considered (specific solutions to hazards) and the repartition was done by hazard.

The first step was the identification of solutions/strategies by all the involved partners (on their respective dedicated fields). Specific workshop and consultation with Open Labs were also organized to identify local and specific solutions/strategies. After classification of all the solutions/strategies identified, partners searched the information expected corresponding to the different fields of the characterization sheets template. Data collection was also organized by partners to carry out LCA and CBA. The information mainly came from the proper expertise of EKO (LCA) and UMAS (CBA) but was completed consulting the partners of T3.4 in relation to the fields that they had in charge.

The characterization data-sheets

Each characterization data-sheet presents the following parameters (from up to down and from left to right), and presented into:

Name of the adaptive solution or strategy: it presents the full and comprehensive name of the related solution or strategy

Prioritization index: corresponds to the value obtained from the prioritization methodology (see The prioritization methodology of listed solutions).

DRM phase (Disaster Risk Management phase): it specifies the disaster risk management phase that the solution can be applied for: prevention, preparedness, response and recovery & BBB.

Hazard: defines for which hazard the solution is valid. More than one hazard can be chosen if the solutions are valid for more than one hazard. Possible selections are Heat waves, Flooding, Earthquakes, Subsidence, Wildfires and Storm.

Action scale: identifies at what level the action can be carried out. Three-action scales are defined:

Building: when the solution is at the structure and/or envelope scale.

District: when the solutions are at urban scale.

Territory: when the solution is at region scale.

Function: identifies the target element of the solution. The characterisation sheet can answer to various compartments of the building itself which are:

Building stabilization: when the objective of the solution is to stabilize the structure and envelope.

Structure stabilization: when the objective of the solution is to stabilize the structure.

Envelope stabilization: wen the objective of the solution is to stabilize the envelope.

Foundation's stabilization: when the objective of the solution is to stabilize the foundations.

Building consolidation: when the objective of the solution is to consolidate the structure and envelope.

Structure consolidation: when the objective of the solution is to consolidate the structure.

Envelope consolidation: when the objective of the solution is to consolidate the envelope.

Foundation's consolidation: when the objective of the solution is to consolidate the foundations.

Urban protection: when the objective of the solution is to protect the urban heritage

Climate adaptation: when the objective of the solution is to allow a better climate adaptation

Water/flood management: when the objective of the solution is to provide protection or adaptation to water or flood

Type of Adaptative Solution (AS): it describes the types of architectural and engineering solution. It can be hard, soft or N/A:

Soft: minimally invasive solution.

Hard: invasive solution.

N/A: Non-Attributed

Then, the second cell provides a deeper description among:

Architectural and engineering solution

Nature-Based Solutions

Technology and tools

Circular economy

Vernacular architecture

Technical needs: it defines the solution from a technical and skill/knowledge point of view. The parameter describes the level of technical requirement for its implementation.

High: high technical solution. Specific skills and/or equipment are needed.

Medium: Medium technical solution. Specific skills and/or equipment might be needed.

Low: low technical solution. Specific skills and/or equipment are not needed.

Cultural/Natural value: Yes/No. It defines whether the solution or the strategy has value from the cultural and natural perspective.

Reversibility: Yes/No/N/A. It defines if the solution or the strategy is reversible and after its implementation, it comes back to an initial state.

Impact on cultural/natural Heritage: Yes/No. Identifies on what element the solution has an impact. If "Yes" is chosen, the affected elements must be selected. This indicator helps to identify what solutions can be implemented on the building or public zone depending on its protection. The selection options are:

Building:

Façade: Material and/or Components and/or Carpentry and/or Color/finishing,

Roof: Material and/or Volume and/or Components,

Structure: Material and/or Structural system,

Public zone: Pavements/material and/or Natural species and/or Path/gradient and/or Parc/natural Environment.

Implementation time: the time needed to implement the solution considering installation and operation time. The implementation time can be:

Short

Medium

Long

Cost: cost of the solution implementation and maintenance (scales will depend on DRM phase and considered fields). The scale is:

Low

Medium

High

Effectivity: identifies if a solution is temporal or permanent. It can influence the selection of the user depending on his objective.

Temporal solution

Permanent

Permanent/mitigate

N/A

Maintenance: it indicates the relative grade of maintenance required for the solution.

Low maintenance: low frequency and low cost;

Medium maintenance: low frequency and high cost or high frequency and low cost;

High maintenance: high frequency and high cost

None: no maintenance is requested

N/A

Disruption of occupancy/use: Disruption time due to the solution implementation. The scale is:

Low <1 week,

Medium 1-2 weeks

High> 2 weeks

Recyclable: if solutions components can be recycled or reused in future interventions. It can be Yes, No, N/A or Part. There is a blank cell below to include there any specific data found for this indicator.

Reusable: if the solution can be used for its implementation in the same or different location.

Yes

No

Part

N/A

CO_2 emissions: see the section of this deliverable explaining how the LCA was carried.

Pictures: descriptive images of the solution.

Description: a brief description of the solution, including the material of the solution.

Other aspects: other positive and negative aspects of the solution. It includes aspects that end-users will use to make a final decision such as:

Impact on HA/HB (Historic Area and Historic Building):

Visual: if the solution alters the aesthetics of the building.

Economic: if the local economy is improved, such as by using local citizens

Social/Cultural: if social and cultural aspects are improved or not. For example, a solution for flooding can be to increase the riverbed, this new river zone can be used to practice sports while there is no flooding risk.

Environmental: when solution impacts on environmental conditions. All issues and trade-offs associated with the solution from a life cycle point of view are explained in this section. Furthermore, the non-LCA benefits identified are also provided in this section.

Success and limiting factors.

Possible combinations with other kinds of solutions.

Life cycle impacts: most important environmental benefits and impacts identified with their severity based on the LCA activities carried out in T3.4. The methodology is presented in Chapter 4.

Non-life cycle impacts: environmental benefits and impacts delivered by the solution that cannot be effectively quantified by the LCA methodology (see Chapter 4).

References: bibliographic references used to get the information on the solution.

Adaptive solution	CLIMBER GREEN WALL					Prioritization Index	5	Shelter	
DRM phase	☐ Emergency	☑ Prevention	☐ Preparedness	☑ Response	☐ Recovery & BBB				
Hazard	☑ Heat waves	☐ Flooding	☐ Earthquakes	☐ Subsidence	☐ Wildfires	☐ Storm			
Action Scale	Building	Function (1)	Climate adaptation	Function (2)					
Type of AS	Hard	Nature-based solutions		Technical requirement	Low				
Impact on cultural value:	Yes			Reversibility	Yes				
Impact on protected CH	Yes	Identify impact on element:							
Building: ☐									
Façade ☐	Material	☑ Components	☐ Carpentry	☑ Colour/finishing					
Roof: ☐	Material	☐ Volumetry	☐ Components						
Structure: ☐	Material	☐ Structural system							
Public zone: ☐	Pavement/ material	☐ Natural species	☐ Path/ Gradient	☐ Parc / natural environment					

Implementation time	Long time	Pictures
Includes the time for the NBS to become fully effective after its implementation (2-4 years, depending on the growth of plants and size of structure)		
Cost	Low	
Investment: 10-120 euros/m² Maintenance: 1-15 euros/m² Cheapest solution regarding investment and maintenance for green walls.		
Effectivity	Permanent solution	
Maintenance	Low	
- No or limited irrigation - Pruning (to keep windows and openings clear and to prevent plants from growing onto the roof and guttering) - 1-2 interventions per year - Less or no sensitive to frost in comparison with other types of green walls		
Recyclable	Yes	
The plants can be composted and the assistance out of steel/wood can be recycled in most cases.		
Reusable	Part	
Impact radius	District	
Disruption of occupance/use [days]	Low	
CO_2 emissions	Low	

Hedera helix (ivy) © Green4Cities

Parthenocissus tricuspidata (Boston ivy) © Green4Cities

Aerial roots Hedera helix © Green4Cities

Sucker discs Parthenocissus tricuspidata © Green4Cities

Climbing plants on a structure © Green4Cities

MFO-Park Zurich © Green4Cities

Different climbing plants on a facade © MA22

Description

This NBS type is about the use of self-climbing plants to cover walls and façades. By this characteristic type, the plant is directly rooted into soil. This is the easiest, cheapest and most efficient way for greening walls and buildings with a long tradition and history. Two main types can be identified, which further split up depending on the botanical properties, i.e. (1) Self-clinging climbers : self-clinging plants do not need any climbing support, because they are growing by themselves with the support of aerial roots (e.g. Hedera helix) or suckers (Parthenocissus sp.), (2) Climbers with supporting system : these climbing plants require a climbing assistance on the building /structure, to climb and hold on it. There are existing supporting systems for nearly any growth form. The climbing assistance has to be adjusted for the right kind of plant.

Material

Climbing plants, Topsoil or substrate. For self-climbing plants no further material is required just a suitable subconstruction (sandy, poisonous, plastic, glass and fresh concrete plasters are not suitable for self-clinging plants). For climbers that need a growing support, specific assistances have to be installed along the wall: wires, steel mesh, threads, etc. (wood support, metal structure). If necessary, fixing for the plant on assistance. Perhaps nutrients.

Other aspects:

Positive aspects:	Negative aspects:
Other direct benefits: Quality of life Significant energy savings in the buildings. Pruning wastes would arise, which might be composted leading to positive circularity effect. Positive effects on climate adaptation, biodiversity, air quality. **Possible combinations with other kinds of solutions :** Combination with solar panels (walls can be partly covered by plants and partly by photovoltaic panels) Combination with bio-materials.	**Impact on HB (Historic Building):** visual (the solution changes the esthetics of the building). Can also be a positive impact. **Possible negative effects:** Presence of undesired insects or allergenic plants, possible damages on the structure or the envelop of the building. Water consumption for irrigation where the amount depends on the plant species. Steel and wire mash are necessary for construction that may lead to climate impacts during their manufacturing. Use of recycled materials would help to avoid such impacts. Chemical consumption during maintenance. Use of fertilizers may create water pollution. **Limiting factors:** - Difficulties of management (for the plants and for the building). The accessibility of the wall is key factor to limit management costs. - Governance and authorizations: building or street owner, maintenance involving co-owners and renter's decisions and payment.

Life cycle impacts

Energy	Water	Waste	Material	Recycling/circularity

Non-life cycle impacts

References

Nature4Cities D1.1 – NBS multi-scalar and multi-thematic typology and associated database, 2018: nbs-explorer.nature4cities-platform.eu/?nbs=GW_climber

Figure 2 Characterization sheet as it can be found into the Portfolio

3.2 The prioritization methodology of listed solutions

The portfolio includes a methodology to provide end-users with a prioritized list of solutions. T3.4 has worked in parallel with T3.3 (Consolidation and structural stabilization in emergency phases). Hence, the methodology developed in T3.3 has been adapted to T3.4 specifications (adaptation and building back better). A brief summary of the methodology is presented below, further information about the link between task can be found in section 2.2.

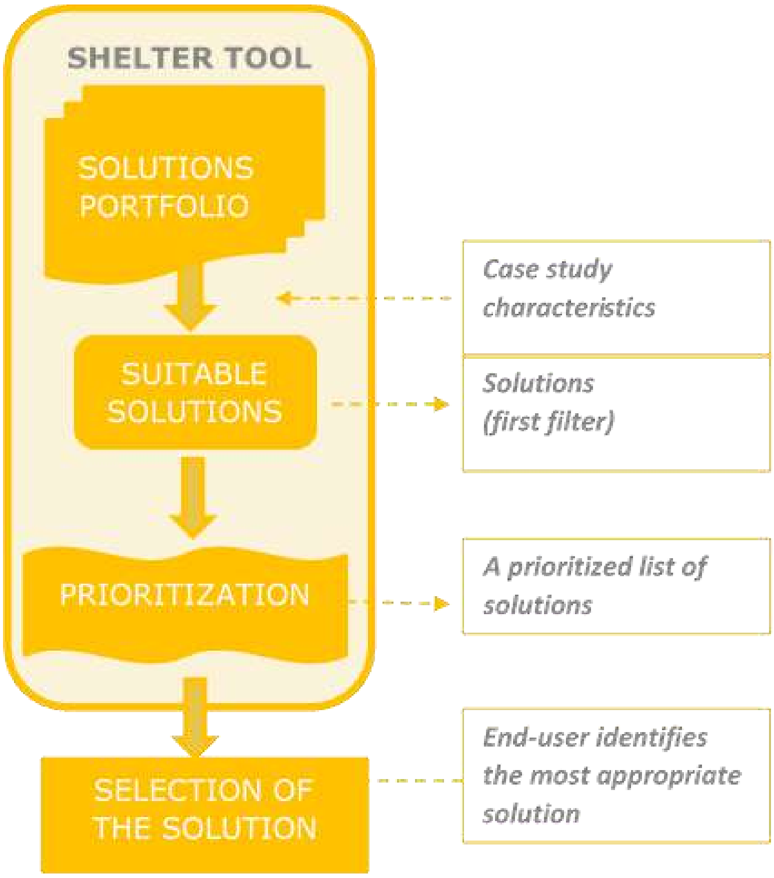


Figure 3 Decision-making process

The prioritization methodology is based on The Integrated Value Model for Sustainable Assessment (Spanish acronym MIVES) methodology which combines multi-criteria decision making and multi-attribute utility theory, incorporating the value function concept and assigning weights through the analytic hierarchy process (AHP). This methodology provides a Prioritization Index (PI) for each solution. For further information see D3.3.

The methodology was developed in five steps: (1) definition of the requirements tree with which the information is organized into a hierarchic structure, (2) assignation of the value functions to each indicator, (3) assignation of the relative weight to each criterion and indicator according to their importance, (4) built a pair-wise comparative matrix for criteria and indicators, and (5) definition of the prioritization index for each solution.

(1) Figure 4 schematises the requirements tree used to obtain the PI.

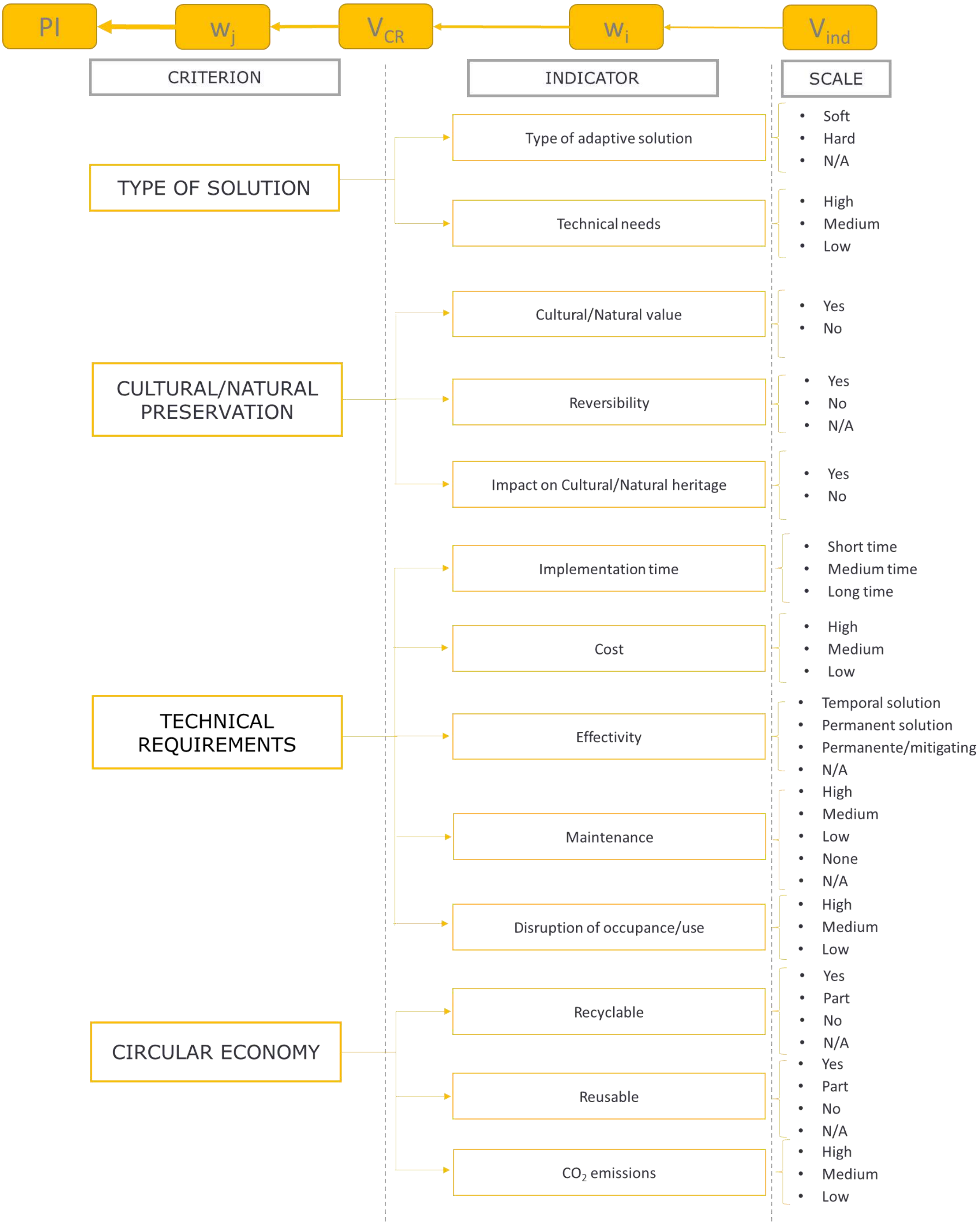


Figure 4 Requirement tree defined for the determination of the PI.

(2) Indicators value according to their value function (**¡Error! No se encuentra el origen de la referencia.**): in this step, the qualitative value is converted into a quantitative value through a value function (V_{ind}). For the definition of the value function eq. (1) and eq. (2) are used. The value function is a dimensionless standardization mechanism that allows a comparison of different dimensional variables which values varies from 0 to 1[73]

$$V_{ind} = B \cdot \left[1 - e^{-k_i\left(\frac{|x-x_{min}|}{C_i}\right)^{P_i}}\right] \quad (1)$$

$$B = \frac{1}{1 - e^{-k_i\left(\frac{|x_{max}-x_{min}|}{C_i}\right)^{P_i}}} \quad (2)$$

Where:

x_{min}; x_{max}.: minimum and maximum reference point on indicator scale (0 and 1 respectively)

x: response to the assessed alternative between x_{min} and x_{max}.

Pi: shape actor curve (concave: <1; convex and "S" shaped>1 and straight≈1)

C_i: abscissa value corresponding to the inflection point on a curve where Pi>1

k_i: C_i point ordinate.

B: standardization factor

Table 1 Indicator value and parameters value for different indicators

	Scale	V_{ind}	Pi	Ci	ki	B
TYPE OF SOLUTION						
Type of AS	Soft	1.00	1	1	0.001	10.5
	Hard	0.00				
	N/A	1.00				
Technical requirement	High	0.00	2.34	47	0.567	1.04
	Medium	0.50				
	Low	1.00				
CULTURAL/NATURAL PRESERVATION						
Impact on cultural value	Yes	0.00	2.9	54	0.55	1.05
	Yes (visibility)	0.00				
	Yes (visibility & integrity)	0.00				
	Yes (integrity, not visible)	0.00				
	No	1.00				
Reversibility	Yes	1.00	2.9	54	0.58	1.05
	No	0.00				
	N/A	1.00				
Impact on protected CH	Yes	0.00	1	1	0.001	10.5
	No	1.00				
TECHNICAL REQUIREMENTS						
Implementation time	Short time	1.00	1	1	0.001	10.5
	Medium time	0.51				
	Long time	0.00				

Cost	Low	1.00	2.9	44	0.561	1.003
	Medium	0.56				
	High	0.00				
Effectivity	Temporal solution	0.00	1	1	0.001	10.5
	Permanent solution	1.00				
	Permanent/mitigating	1.00				
	N/A	1.00				
Maintenance	None	1.00	2.9	45	0.55	1.01
	Low	1.00				
	Medium	0.53				
	High	0.00				
	N/A	1.00				
Disruption of occupancy/use	Low	1.00	2.9	55	0.58	1.05
	Medium	0.37				
	High	0.00				
CIRCULAR ECONOMY						
Recyclable	Yes	1.00	2.5	35	0.47	1.005
	Part	0.69				
	No	0.00				
	N/A	1.00				
Reusable	Yes	1.00	2.5	35	0.45	1.005
	Part	0.67				
	No	0.00				
	N/A	1.00				
CO_2 emissions	Low	1.00	2.9	50	0.555	1.017
	Medium	0.43				
	High	0.00				

(3) The weight for criteria and indicators has been obtained through a survey to OLs experts (Table 2)

Table 2 Mean value of the responses to the survey

	Sava River Basin OL	Ravenna OL	Galicia OL	Dordrecht OL
Number of survey responses per (OL)	11	15	2	1
TYPE OF SOLUTION	6.69	7.80	7.50	8.00
Type of adaptive solution	6.69	7.93	7.50	7.00
Technical needs	6.62	7.60	7.50	6.00
CULTURAL/NATURAL PRESERVATION	7.15	8.40	8.50	8.00
Cultural/Natural value	6.92	8.53	8.00	8.00
Reversibility	6.08	8.27	7.50	8.00
Cultural/Natural heritage	7.38	8.13	9.00	9.00
TECHNICAL REQUIREMENTS	6.62	7.87	6.50	6.00
Implementation time	6.23	6.87	5.50	4.00
Cost	5.69	7.07	5.00	7.00
Effectivity	6.62	8.40	8.00	8.00
Maintenance	6.92	8.07	7.00	7.00
Disruption of occupancy/use	6.00	6.87	6.00	8.00
CIRCULAR ECONOMY	5.69	7.20	6.50	7.00
Recyclable	5.77	7.13	5.50	5.00
Reusable	6.38	7.07	4.00	6.00
CO_2 emissions	6.15	6.93	9.00	6.00

(4) The relative importance to each criterion and indicator (Table 3) is defined by means of the comparative matrix (for further information see D3.3).

Table 3 Criteria/indicators relative weight value.

	Sava River Basin	Ravenna	Galicia	Dordrecht
TYPE OF SOLUTION	0.26	0.25	0.26	0.28
Type of adaptive solution	0.50	0.51	0.50	0.54
Technical needs	0.50	0.49	0.50	0.46
CULTURAL/NATURAL PRESERVATION	0.27	0.27	0.29	0.28
Cultural/Natural value	0.34	0.34	0.33	0.32
Reversibility	0.30	0.33	0.31	0.32
Cultural/Natural heritage	0.36	0.33	0.37	0.36
TECHNICAL REQUIREMENTS	0.25	0.25	0.22	0.21
Implementation time	0.20	0.18	0.17	0.12
Cost	0.18	0.19	0.16	0.21
Effectivity	0.21	0.23	0.25	0.24
Maintenance	0.22	0.22	0.22	0.21
Disruption of occupancy/use	0.19	0.18	0.19	0.24
CIRCULAR ECONOMY	0.22	0.23	0.22	0.24
Recyclable	0.32	0.34	0.30	0.29
Reusable	0.35	0.33	0.22	0.35

CO_2 emission	0.34	0.33	0.49	0.35

(5) Prioritization Index. (PI). The PI depends on the indicator value and the relative weight of the criteria and indicators, and it is obtained according with equations EQ. (3) and EQ. (4). EQ. (4) represents the value of each criterion obtained with the relative weight of respective indicator and their value. Ec. (3) is the PI obtained with the value and the relative weight of each criteria.

$$PI = \sum V_{crit.j} \cdot w_j \tag{3}$$

$$V_{crit.j} = \sum V_{ind.i} \cdot w_i \tag{4}$$

Where:
w_i: relative weight of each indicator.
$V_{ind.i}$: indicator value obtained from EQ. (1). Values are summarized in **¡Error! No se encuentra el origen de la referencia.**.
V_{crit}.: value of each criteria
w_j: relative weight of each criteria

There are two assessment options for the PI. Each assessment option includes the three scales.

1. <u>PI based on case study characteristics:</u> pre-defined scenarios are created-The next table summarizes the weights of each criterion/indicator according to these options (**¡Error! No se encuentra el origen de la referencia.** of the appendix summarizes the solutions with the different PI according to the pre-defined scenarios):
   - PI at territory scale: the PI is based on the results gathered in Galicia and Sava OLs. These OLs include the characteristics and needs of territory-scale case studies.
   - PI at urban scale: the PI is based on the results gathered in Dordrecht OL. This OL includes the characteristics and needs of urban scale case studies.
   - PI at building scale: the PI is based on the results gathered in Seferihisar and Ravenna OLs. These OLs include the characteristics and needs of urban scale case studies.

Table 4 The weight of each criterion/indicator based on case study characteristics

	Territory scale	Urban scale	Asset scale
TYPE OF SOLUTION	0.26	0.28	0.25
Type of adaptive solution	0.50	0.54	0.51
Technical needs	0.50	0.46	0.49
CULTURAL/NATURAL PRESERVATION	0.28	0.28	0.27
Cultural/Natural value	0.34	0.32	0.34
Reversibility	0.30	0.32	0.33
Cultural/Natural heritage	0.36	0.36	0.33
Building:	0.25	0.50	0.75
Façade	0.33	0.33	0.33
Material	0.50	0.50	0.50
Components	0.26	0.26	0.26
Carpentry	0.16	0.16	0.16
Colour/finishing	0.08	0.08	0.08
Roof:	0.33	0.33	0.33
Material	0.43	0.43	0.43
Volumetry	0.43	0.43	0.43
Components	0.14	0.14	0.14
Structure:	0.33	0.33	0.33
Material	0.50	0.50	0.50
Structural system	0.50	0.50	0.50
Public zone:	0.75	0.50	0.25
Pavement/material	0.10	0.28	0.46
Natural species	0.37	0.12	0.17
Path/Gradient	0.17	0.47	0.27
Park / natural environment	0.37	0.12	0.10
TECHNICAL REQUIREMENTS	0.25	0.21	0.25
Implementation time	0.19	0.12	0.18
Cost	0.18	0.21	0.19
Effectivity	0.22	0.24	0.23
Maintenance	0.22	0.21	0.22
Disruption of occupance/use	0.19	0.24	0.18
CIRCULAR ECONOMY	0.22	0.24	0.23
Recyclable	0.31	0.29	0.34
Reusable	0.33	0.35	0.33
CO_2 emission	0.36	0.35	0.33

2. PI based on end-user preferences: end-users have the opportunity to define the relative weight for each criterion and each indicator according to their preferences.

4 Solutions Life Cycle Assessment (LCA)

4.1 Description of the development of the LCA methodology

Climate change creates many tangible and intangible impacts on anthropogenic and natural systems including the heritage sites leading to loss of biodiversity, deterioration of archaeological sites and loss of cultural heritage (CH) sites through increased erosion and flooding [1]. Additionally, rapidly increasing population in cities create added stress on historically significant built environment. Ultimately, climate change increases the vulnerabilities of heritage sites, which necessitates the conservation of these sites in a sustainable manner.

As a part of SHELTER Project, tools and solutions for prevention, preparedness, response and recovery (WP3) are being characterized and developed for cost-effective low carbon technological solutions to be utilized to promote building back better (BBB) approach. Within the framework of technical activities under WP3, **life cycle assessment (LCA)** is utilized in a qualitative manner to **ensure low carbon characteristics of spatial interventions, construction activities and other material flows**.

Current section aims to

- Investigate **applicability of LCA** within the scope the cultural heritage conservation and DRM for improved resilience
- Provide a **qualitative analysis of life cycle impacts** of a number of low carbon technologies
- Offer **recommendations** for the application and integration of LCA in conservation and DRM activities.

The scope of the LCA-based assessment covers all the solutions presented in Chapter 3.

4.1.1 Life cycle thinking and LCA

Although life cycle thinking has been already adopted and accepted as state-of-the-art methodology for evaluating various environmental impacts, particularly within industrial domains, the application of LCA in the context of CH and DRM are relatively new. The overall impact of cultural heritage efforts in terms of resource consumption has been overlooked until recently. However, as in the case of all urban activities, projects aiming to preserve cultural heritage has their environmental footprint. All the measures taken for cultural heritage projects as well as disaster prevention or response have the potential to consume materials and energy and generate waste. LCA can be a robust support tool to select between different solutions, plan and implement them in an environmentally friendly manner. For this purpose, an introduction to important concepts related to LCA is provided in this section for the readers unfamiliar with LCA.

Life Cycle Thinking (LCT) is defined as "going beyond the traditional focus on production site and manufacturing processes to include environmental, social and economic impacts of a product over its entire life cycle" [4]. The main incentive to adopt LCT is to facilitate the links between environmental, social and economic dimensions of the system studied and support sustainable development. LCT encompasses evaluation of the life cycle of product and service systems from different aspects establishing **a holistic framework** for understanding production and consumption activities. Currently, three assessment methodologies are available to practitioners that allow complimentary analysis from a life cycle perspective. These include **life cycle assessment (LCA)** for environmental impacts, **life cycle costing (LCC)** for economic implications and **social life cycle assessment (S-LCA)** for the social dimension.

Life cycle assessment determines the potential environmental impacts (e.g., use of resources and environmental consequences releases) throughout a product’s life cycle from raw material acquisition through production, use end-of-life (EoL) treatment and final disposal (i.e., cradle-to-grave) [5].

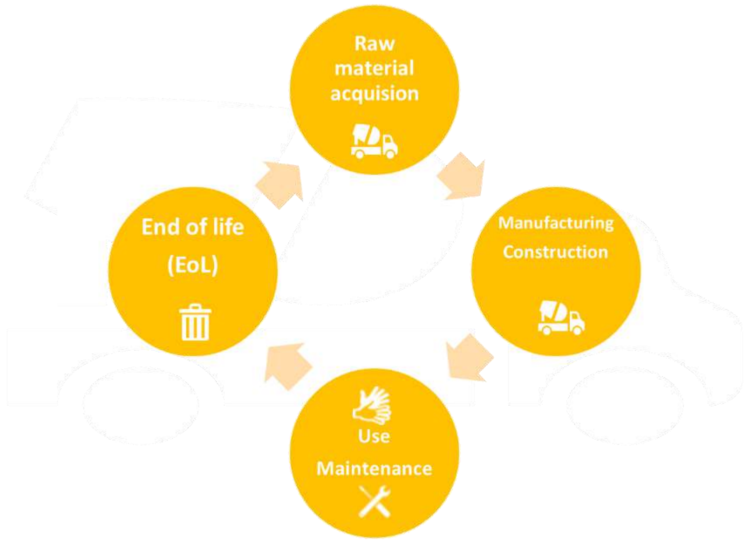


Figure 5 Life cycle stages covered by LCA

As a widely accepted methodology to quantify a range of environmental impacts, LCA has been applied to many sectors previously. Two ISO standards (ISO 14040:2006 and ISO 14044:2006) exist for robust and systematic implementation of LCA in different domains [5][6].

LCA can assist in

- Identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- Informing decision-makers in industry, government, or non-governmental organizations or the purpose of strategic planning, priority setting, product or process design/redesign,
- Selecting relevant indicators of environmental performance, and
- Marketing including environmental claims (e.g., Environmental product declarations) [5].

Basically, LCA relies on the determination of the inputs in terms of material and energy as well as outputs in the form of products, co-products and all releases to the environment, which then analysed in terms of their impacts on different compartments of the environment and damages created on human and natural ecosystems.

According to these standards, LCA studies follow 4 stages as shown in Figure 6.

A short description of the stages of LCA are provided below:

1. *Goal and scope definition*: As a first step, goal and scope definition of each LCA study is established by the practitioner. While the goal setting involves the intended application, reasons for carrying out the study and intended audience, the scope addresses the product system to be studied, functions of the product system, functional unit of the study, system boundaries, allocation procedures, impact categories and impact assessment methodologies utilized, assumptions and limitations.
2. *Inventory analysis*: It involves data collection and calculation of procedures to quantify relevant material- and energy-based inputs and outputs of a product system, which can be a product, a production system or a service[1].
3. *Impact assessment*: This phase aims at evaluating the significance of potential environmental impacts using the inventory results, associating the inventory data with specific environmental impact categories and indicators.
4. *Interpretation*: In this last step, the findings from inventory analysis and impact assessment are considered together to reach conclusions such as environmental hot spots or dominant environmental impacts.

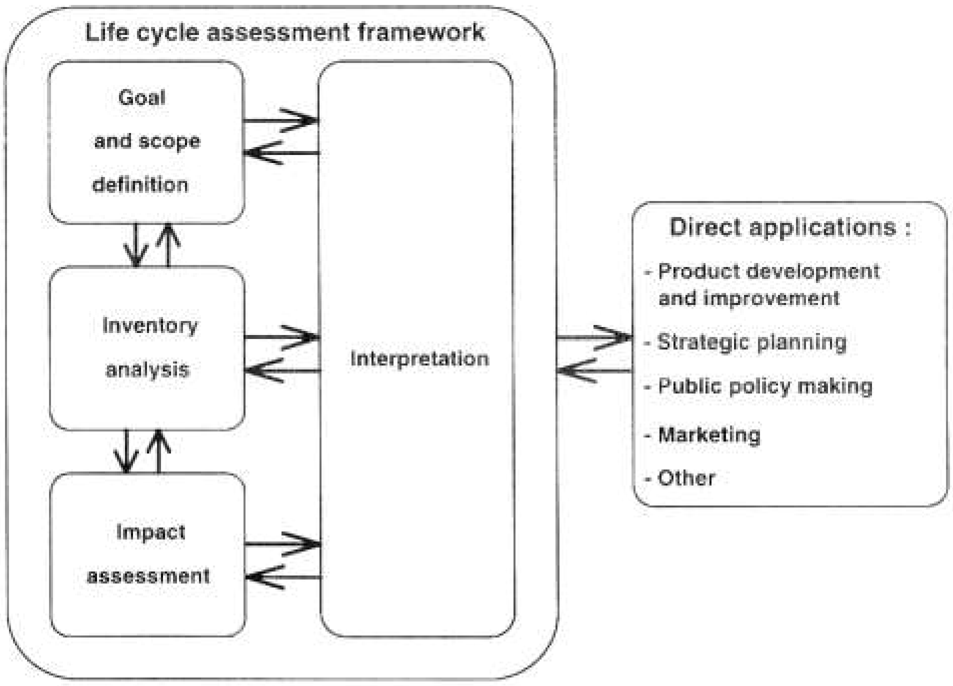


Figure 6 Stages of LCA [5]

[1] In the context of CH and DRM, product system refers to the solutions within the portfolio.

One of the strengths of LCA methodology is that it allows development of scenarios with identical functions and **scenario comparisons** in terms of products, technologies or services used to obtain intended function, which makes LCA a strong **decision-support tool**.

It is important to underline that although in its infancy, the main focus of LCA was industrial products and manufacturing, in time, LCA has been applied to many areas beyond the industrial domain. In fact, the definition of the "product system" in ISO standard encompasses any goods or services, the latter having tangible and intangible elements. Still, LCA faces certain limitations to present some intangible outputs of services as, methodologically, all inputs and outputs of the system studied should be linked to physical inventories. However, as will be presented in the next section, the use of LCA for CH and DRM is increasing with methodological recommendations being made to close the gaps for sound application of LCA in these areas.

4.1.2 Current status of applicability of LCA for CH and DRM

4.1.2.1 LCA for DRM

Destruction of modern built environment resulting from natural disasters has increased due to the repercussions of climate change and rapid urbanization in hazard-prone areas [7]. LCA studies under DRM are related to the implementation of preventive technologies and post-disaster response for earthquakes, floods and stormwater management. They can be used to determine the real-life cycle impacts of disasters, identify hotspots in terms of materials and processes applied and finally facilitate informed decision making among different disaster mitigation activities. In this sense, LCA can become beneficial for benchmarking performance and support cost-benefit assessment (CBA) by clearly separating costs from benefits [8][9]. For flood management, LCA has been proposed to actively support decision-making process from the point of design and help to communicate stakeholder perspectives and priorities with respect to different flood safety levels to provide valuable information during the planning process [10]. Brudler and. al. (2016) demonstrated this by using LCA to assess the environmental impacts of a stormwater management system, comprised of green infrastructure and local retention measures in combination with the planned routing of stormwater on the surfaces to manage runoff and compared it to a traditional, sub-surface approach. Their study was able to show that the stormwater management system created lower impacts than the traditional alternative at the planning stage [10].

Wei et.al. (2015) conducted a cradle-to-grave[2] LCA study to develop a framework that can quantify environmental impacts of building damage and both pre-seismic structural retrofitting and post-seismic rehabilitation of buildings [7]. They propose that, particularly in risk-prone areas, the sustainability of buildings can be affected by disastrous events such as earthquakes and extreme events caused by climate change exacerbates this situation [7]. Earthquake damage to a building or to any built

[2] Cradle-to-grave LCA studies refer to inclusion of all life cycle phases of raw material acquisition (cradle), manufacturing/construction type operations, use of product or service and EoL with final disposal (grave).

environment for that matter leads to environmental loss, requires demolition and re-building or retrofit and therefore, changes the life cycle building performance as well as their long-term sustainability.

Wakabayashi et.al. (2017) focused on this aspect and developed an LCA and LCC methodology for an integrated disaster waste processing system involving earthquake and tsunami debris [11]. Optimization was carried out to make the selection between different waste management options. Considering the vast amounts of concrete, wood and glass debris generated as a result of natural disasters like earthquake and associated environmental burdens to manage them, the study concludes that pre-seismic retrofitting and upkeeping of flood prevention should be prioritized. In their single score LCA study for a real Italian case evaluating the reverse network performances of different waste management strategies, Daria et. al. (2015) proposes re-use of the earthquake debris as environmentally friendly end-of-life (EoL) option [12].

Hosseini et. al. (2019) conducted a cradle-to-grave assessment of temporary housing to choose the most suitable building technology for post-disaster intervention [13]. In addition to environmental indicators related to water and energy consumption as well as carbon emissions, the authors suggested the use of a sustainability index consisting of implementation and maintenance cost, safety, customization, resource consumption, and emissions.

Another DRM area that is closely associated with climate change is storm water management, where potential environmental hotspots can arise due to infrastructure to collect stormwater including the construction materials of steel or concrete with embodied burdens as well as treatment of the collected wastewater. Angrill et. al. (2016) conducted a mid-point LCA for the rain water harvest system covering its whole life cycle [14]. LCA results showed that among different scenarios, a rooftop tank satisfying ground level laundry water demand delivers the lowest environmental impacts.

Grubert and Stokes-Draut (2020) underline the disparity between the environmental impact the DRM infrastructures aim to improve versus the environmental impacts they create [9]. For this reason, they conclude, it is important to employ multi-criteria assessment methodologies such as LCA than to concentrate on singular issues. This can be particularly important for avoiding any misleading conclusions drawn by decision-makers. At the same time, caution is warranted when communicating LCA results with a non-LCA audience to prevent erroneous conclusions for investment in mitigation infrastructure [9].

Petit-Boix et. al. (2017) integrated flood damage prevention measures of swales, filters and infiltration trenches into LCA to quantify net environmental impacts and environmental payback [18]. Similar to Wakabayashi et. al. (2017), the authors stipulate the importance of preventive measures in avoiding the destruction of goods that would otherwise be damaged, however, they are also underlining the difficulties for predicting future damage in specific locations.

4.1.2.2 LCA and Climate Adaptation

Studies on nature-based solutions (NBS) and urban heat island (UHI) effect are increasing in number, which combine LCA and climate adaptation.

As energy consumption measures, Cubi et. al. (2015) assessed a number of building rooftop options applied in Canada including white roofs, green roofs and photovoltaic panels [15]. Among these alternatives, the photovoltaic panels proved to be the best performing technology in all impact categories. On the other hand, green roofs resulted in net positive impacts in most of the impact categories including GHG emissions. White roofs had net negative impacts in most categories, which yield to the conclusion that they do not deliver environmental advantage, especially in cold climates. In another study investigating rooftop NBS techniques by El Bachawati et. al. (2016) vegetated roofs with gravel ballasted roofs and white roofs were compared on a cradle-to-gate basis [16]. The results suggest that the extensive green roofs delivered the lower environmental impacts in all 15 impact categories. Climatic conditions and electric grid mix created regional sensitivities. Gargari et. al. (2016) explains the difference between green roof techniques as the depth and type of medium soil, type of vegetation requiring different levels of maintenance and irrigation [17]. According to this study, extensive green roof systems were found to have fewer environmental impacts. These impacts are suggested to be even further lowered if the number of recycled materials can be used in the growing medium and the membranes.

Another NBS investigated for the building energy efficiency is the living wall systems where they are considered to bring insulation and cooling properties (in Mediterranean climate) that lead to energy savings [20]. Ottelé et. al. (2011) compared a number of façade configurations including brick, directly greened, indirectly greened (with steel mesh support) as well as living wall systems with planter boxes and felt layers [20]. The results indicate the net environmental impacts depend on the configuration of the living wall system and the climatic conditions at the site of implementation. With respect to the configurations, the environmental impact originating from implementation increases as the requirement for raw materials such as support systems increases. When this NBS type is being applied, conducting LCA studies are advised particularly for temperate climates where environmental impacts of implementing living wall systems may outweigh the benefits delivered as a result of energy savings. For Mediterranean climate zones, where additional benefits can be obtained for cooling, LCA studies still prove to be beneficial to estimate net environmental impacts and choose between different configurations [20].

Green urban spaces are among the NBS that has been widely used for climate adaptation apart from other benefits like recreational opportunities, air pollution control and maintaining urban biodiversity. One study that was conducted to assess life cycle impacts for green spaces is from Strohbach et. al. (2012) and focuses on the carbon footprint rather than the whole range of life cycle impacts [21]. The case study used was selected as a green space project constructed in Leipzig, Germany. During the life cycle assessment of urban green spaces, which are constructed, planted and maintained by humans, environmental trade-offs created by fossil fuel consumption due to maintenance equipment and vehicles, irrigation, fertilization and transportation of materials should be considered, which causes GHG emissions.

The applicability of LCA for studying urban heat island (UHI) effect was also investigated. According to the literature review by Belussi and Barozzi (2015), mostly the UHI related LCAs focused on the carbon reduction potential of UHI mitigation technologies applied on buildings, pavements and urban green spaces with varying scope, service life and system boundary definitions [22]. Some studies consider the whole buildings while others narrow the scope down to specific technological solutions. Additional considerations include runoff management, reduction of the UHI effect and improvement of the air quality. It has been observed that due to differences in defining scope and system boundary, it is challenging to compare different LCA studies on this topic.

In a recent study, Susca and Pomponi (2020) argue that existing studies on LCA targeting the UHI mitigation technologies fail to address the mutual interactions between the built environment and local climate and the consequent impacts on human health and ecosystems and underline the necessity to focus on building and street dimension not only for the development of life cycle inventories but also in terms of life cycle impacts [23]. For this purpose, they propose a new impact category called **local warming potential** to capture the variation in urban temperature and model microscale phenomena of UHI [23].

4.1.2.3 LCA and Cultural Heritage

Although its application is rather new to the cultural heritage experts, LCA is gaining traction within CH management area.

One of the few studies in this area is conducted by Settembre Blundo et. al. (2018) is to validate a conceptual protocol for "Cultural Heritage Life Cycle Management" seen in Figure 7 and build an operational model for the design and monitoring of restoration work on the Cultural Heritage in accordance with the three pillars of sustainability [24]. It is proposed that application of life cycle sustainability assessment in cycles, where it is not only used at the initial decision-making phase but also repetitively during valorization (i.e., operational) phase after conservation works are finished, transform the CH management from a linear process to a circular one. This brings CH management one step closer to life cycle thinking.

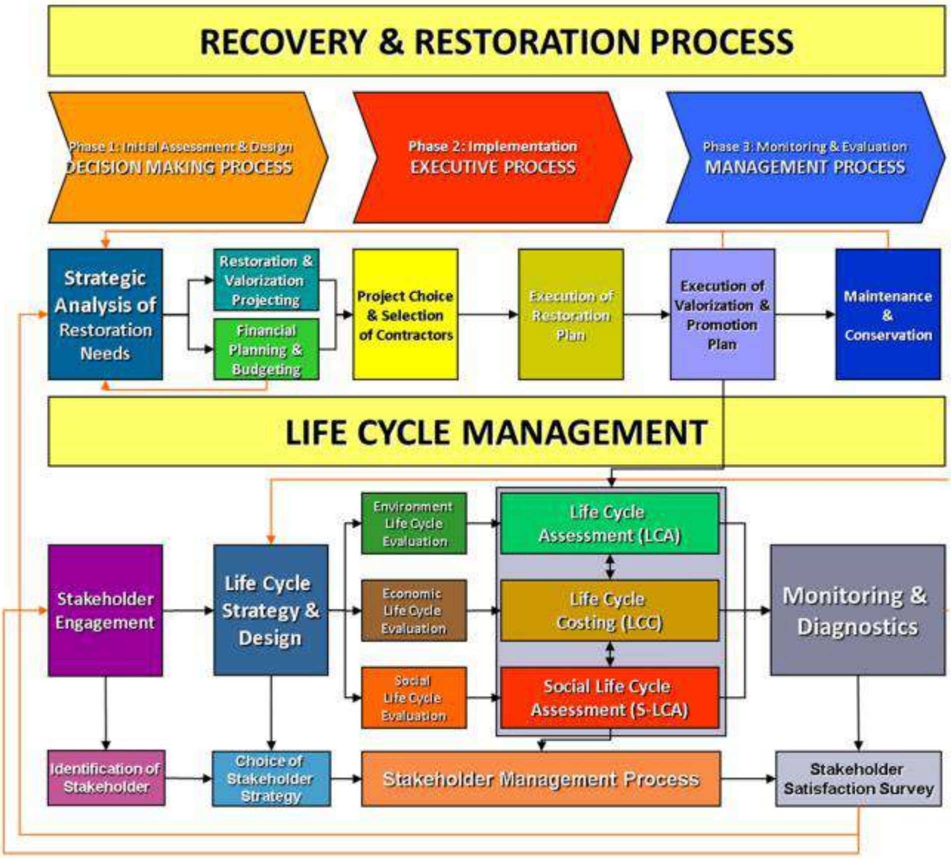


Figure 7 Protocol of Cultural Heritage–Life Cycle Management [24]

Karoglou et. al. (2019) used LCA to select between restoration options (restoration materials and specifically plaster and insulation materials) for a building stock of a deteriorated refugee social housing complex dating from the interwar period [25]. The authors argue that due to the commonality of tensions and conflicts between preservation-related decision-making and sustainability goals, there is a need to identify and integrate new "eco-friendly" materials[3] in the field of the protection of built cultural heritage, considering not only the compatibility of the various conservation interventions but also the environmental footprint of these interventions. As a result of the LCA, this study concludes that low environmental footprint insulation materials in the restoring process can lead to significant environmental gain since these old buildings.

4.1.2.4 LCA and Circular Economy (CE)

In its essence, the circular economy concept can interest CNH management in a number of ways

- Extending the lifetime of goods and assigning them new functions, which in line with prolonging the lifetime of cultural assets
- Re-design/re-thinking of cultural heritage, true to its origin yet converging to a lower environmental footprint during restoration and use

[3] This discussion can be effectively expanded to other areas of restoration such as the restoration chemicals used for art works.

- Consideration of reuse/recycling options both for the raw materials consumed and wastes generated during restoration.
- Valorisation and shared use of existing goods with new functions
- Re-creation of value through the use of parts of existing (ancient, historical) buildings (refurbishing/remanufacturing) [26].

Rather than a wide review of LCA of CE economy models, which are abundant due to the long history of waste valorisation within industrial and urban domains, this subsection focuses on the small number of studies combining CE and CH management.

Tomesetta (2017) studied LCA and CE as support instruments for CH management [27]. While as a new paradigm, CE, brings a fresh look at industrial ecosystems and emphasized the decoupling of resource consumption and environmental impacts, particularly with increased consideration for EoL materials (i.e., wastes) as resource. The author argues that CH field is lacking a clear perspective and instrument to support conservation management decisions and effects for the emissions associated with conservation activities/materials. In order to achieve sustainable CH conservation, it is necessary to select safe materials and methods both in terms of human and environmental health but also quantify the benefits deriving from the conservation process. For this purpose, any added value potentially created by circular economy solutions should be taken into consideration during decision making.

In a recent study, conducted in 2020, Foster et. al., underlines the relevance of ISO 212929-1:2011 Sustainability in building construction, which identifies global warming potential, ozone depletion potential, non-renewable resource consumption, fresh water consumption, waste generation, access to facilities such as public transport, adaptability and maintainability as core indicators for sustainable buildings [28]. Furthermore, as pointed out within this study, the new reporting framework of the EU, Level(s) aims to "help construction and real estate stakeholders to reduce the environmental impacts of the buildings they invest in, design, build and occupy, by providing them with a reporting framework that links the building's individual performance with European policy objectives " [29]. While LCA is proposed as the suitable methodology to determine the sustainability of buildings, Foster et. al. (2020) conclude that the indicator scope of Level(s) is sufficiently broad that it would apply to cultural heritage buildings.

4.1.3 Guidelines for including LCA within CH and DRM

The audience for LCA studies within the DRM domain can be listed as urban planners, decision-makers including municipalities and local governments and insurance companies [18].

4.1.3.1 System boundaries

In most ideal cases, the possibilities to conduct **cradle-to-grave** LCAs should be pursued based on the fact that **EoL (End of Life)** of applied solutions or the baseline scenarios (no solution is applied for preparedness or response) can impact the LCA results. According to Brudler et. al. (2016), while economic evaluations are frequently employed, LCAs with a cradle-to-grave approach are less frequent in the stormwater management area [10]. For earthquake-related studies, the findings indicated that the environmental impacts of managing debris from demolition activities of buildings can be significant and should be included within the system boundaries of life cycle assessment studies [7]. Particularly, for the solutions implemented on the historic buildings, which have poor energy efficiency, the improvement in the **operational performance** of buildings can help to offset adverse climate impacts of restorative construction processes. This is also valid for a number of NBS solutions applied on building including green roofs and green walls. In these cases, it is important to include the **building energy savings** within LCA to determine the complete range of benefits created [17].

One of the most important aspects of LCA is to conduct **scenario comparisons** between no-action cases and/or between different solution applicable. During scenario comparisons, it is mandatory to construct scenarios with **identical functions**. In no-action cases, the scenarios should include post-disaster responses to restore environmental or cultural assets to their original condition. For comparisons between different solutions, all should deliver the same services in terms of environmental, social and economic aspects.

Based on the literature review delivered by Grubert and Stokes-Draut (2020), when LCA studies aim to determine and compare the impacts of DRM infrastructures, comparisons should be done on the basis of the same mitigation targets [9]. Furthermore, secondary functions of the DRMs should also be considered during comparative LCA [10], with system expansion applied whenever needed. All alternatives have to provide the same primary function, as defined and quantified in the functional unit, to allow a comparison of environmental impacts. One of the advantages of implementing comparative LCA is to be able to correlate single or combination of technologies. The importance of this aspect is underlined particularly for flood management, where usually a combination of different measures and elements is necessary over the whole catchment [10]. For cross-system comparisons, **normalizing** the environmental impact of mitigation by the mitigation function itself can be an effective way of enabling clear communication of LCA results.

4.1.3.2 Functional unit

Potential **functional units** for LCA studied can be selected as:

- Performance-based functional unit (Unit of environmental burden mitigated);
- Capacity-based functional unit (Capacity, size, or equivalent unit of infrastructure);
- Production-based functional unit (Unit of output of the harm-causing product system) [9].

For green roofs, a functional unit can be selected as 1 m2 of roof with appropriate service life identified [17]. Similarly, a functional unit of 1 m2 wall area can be used for living wall systems [20]. Strohbach et. al. (2012) selected as the mass of CO2 for their urban green space LCA [21].

4.1.3.3 Life cycle inventories

Data collection is a very critical step in LCA as **case-specific information** is always required. Gargari et. al. (2016) highlighted **a general lack of specific life cycle inventory** information for green roofs that leads to a potential inaccuracy of the assessment especially when recycled materials are used in the growing medium or when disposal scenario includes recycle processes [17]. This observation is very much valid for the majority of DRM activities and cultural heritage management projects. Domain-specific inventories can only be compiled and validated over time.

In addition to case-specific inventory data, circumstantial conditions such as total area, topography, superficial and underground installations, building types and average rainfall patterns for flood management can play a role in the determination of life cycle impacts. There are also important challenges to determine future changes within the system boundaries accurately [18]. Plevin et. al. (2013) cautions about the potential underestimation of environmental impacts of climate adaptation solutions as a result of truncation of LCA system boundaries due to data gaps and practical limitations [30]. This observation further underlines the importance of case-specific information.

In order to compile life cycle inventories for DRM, urban metabolism approach can be useful. Urban metabolism (UM) is a promising assessment approach that relies on the determination of urban flows and stock using a material flow analysis approach, which can easily be translated into life cycle inventories [31][32]. This approach was utilized in the Nature4Cities Project in order to determine the environmental impacts of NBS by using urban metabolism for the generation of material, energy and waste data for indicator-based assessment. Again, in this project, urban metabolism approach was utilized as a way to collect life cycle inventories for LCA of NBS [33]

4.1.3.4 LCA indicators

One of the main strengths of LCA is its capability to assess multiple environmental impacts simultaneously and to identify potential trade-offs. Information on these trade-offs become valuable to influence the design process at early stages [10].

The multiple environmental impacts are reported in the form of life cycle indicators, some of which are directly related to the material or energy used while others represent a form of impacts created on environment such as acidification linked to emission of acidifying substances to air which subsequently increase the acidity in water bodies or eutrophication of water bodies by the release of nutrients to environment without treatment.

According to ISO 14040-44 Standards, the most relevant environmental impacts need to be reported. Therefore, it is the responsibility of the LCA practitioner to identify and discuss these relevant impacts/indicators on a case-by-case basis during the interpretation stage of LCA. In order to provide guidance, some LCA indicators used in previous LCA studies are presented in Table 5. As can be seen from this table, while some studied concentrated on a more limited number of indicators, others concluded that a wider range of indicators is relevant for their purpose. The latter is usually valid when a number of different raw materials are employed or different wastes to be managed via various EoL treatment scenarios. Furthermore, for instance, electricity consumption (thus energy generation) or transportation activities can cause a variety of impacts to occur.

Table 5 Life cycle impact categories used in the literature studies

Life cycle impact categories	Study	Reference
Earthquakes		
Embodied energy, CO_2 emissions	Wei et.al. (2015)	[7]
CO_2, SO_x, NO_x, and PM emissions	Wakabayashi et.al. (2017)	[11]
Water and energy consumption, waste generation, CO_2 + LCI	Hosseini et. al. (2019)	[13]
Flooding and stormwater management		
climate change, ozone depletion potential, terrestrial acidification potential, freshwater eutrophication potential, marine eutrophication potential, human toxicity potential, photochemical oxidant formation potential, water depletion potential, metal depletion potential and fossil depletion potential, the cumulative energy demand	Petit-Boix et. al. (2017)	[18]
Climate change, ionising radiation, photochemical oxidant formation, freshwater eutrophication, marine eutrophication, resource depletion (fossil), terrestrial acidification, terrestrial eutrophication	Brudler et. al. (2016)	[10]
Abiotic depletion potential, acidification potential, eutrophication potential, global warming potential, human toxicity potential, ozone depletion potential, and photochemical ozone creation potential	Angrill et. al. (2016)	[14]
NBS		
Carginogens, non-carcinogens, respiratory organics and inorganics, aquatic and terresterial eco-toxicity, terrestrial and aquatic acidification, eutrophication, global warming, non-renewable energy	Cubi et. al. (2015)	[15]
All midpoint and endpoint indicators	El Bachawati et. al. (2016)	[16]
Global warming potential, ozone depletion, acidification for soil and water, eutrophication, photochemical ozone creation POCP, depletion of abiotic resources-element, depletion of abiotic resources – fossil fuels	Gargari et. al. (2016)	[17]
Abiotic depletion, global warming, ozone layer depletion, human toxicity, fresh water aquatic ecotoxicity, marine water aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, eutrophication	Ottelé et. al (2011)	[20]
CO2 footprint	Strohbach et. al. (2012)	[21]
Climate adaptation and UHI		
Local warming potential – new indicator proposed	Susca and Pomponi (2020)	[23]
Cultural heritage		
global warming potential, ozone depletion potential, non-renewable resource consumption, fresh water consumption,	Foster et. al. (2020)	[28]

waste generation, access to facilities such as public transport, adaptability and maintainability		
Acidification Potential, GWP, ozone depletion potential, human toxicity, ecotoxicty, freshwater and marine eutrophication, particulate matter, photochemical ozone formation, fresh water consumption	Karoglou et. al. (2019)	[25]

Grubert and Stokes-Draut (2020), Efroymson et. al. (2004) and Petit-Boix et. al. (2017) argue the use of **net environmental benefits**, which is "the gains in the value of environmental services or other ecological properties attained by disaster risk mitigation, remediation or restoration minus the value of adverse environmental effects caused by those actions" [9][18][19].

4.1.4 LCA methodology within SHELTER Project

SHELTER project is concerned with a high number of solutions addressing different hazards, which can be applied at different DRM phases. The aim of the LCA-based approach established in T3.4 is to provide a general understanding of the life cycle impacts and hotspots for this wide range of solutions. This qualitative assessment will guide the future LCA studies, which needs to be conducted on a case-by-case basis by gathering specific material and energy inventories.

The basis of the LCA approach was to determine the hotspots from a life cycle point of view for the domain experts and LCA practitioners to take into account in future studies. These hotspots are life cycle inventory analysis-oriented and include:

- Energy consumption
- Water consumption
- Waste generation
- Material consumption
- Recycling/circularity

The corresponding environmental impacts for each category is highly dependent on the type of material (such as chemicals or mineral raw materials) and energy (renewable or fossil sources for energy generation) used, the origin of water consumed and type of end of life (EoL) treatment necessary for various wastes. Therefore, only through case-specific LCA studies, exact environmental impacts can be quantified. For this reason, only general inferences are provided in the following sections of this deliverable.

In addition to notable LCA hotspots, information on in which the life cycle stages the hotspots are occurring is also specified. These stages, as shown in Figure 8, covers raw material acquisition (cradle), manufacturing of raw materials as well as construction stage of the solution, use phase and the maintenance and finally EoL stage (grave) where the solution is no longer in service. Generally, the use and maintenance are handled jointly in LCA studies, however, for this task, they are taken into consideration separately to inform the readers about the distinction between the material consumption for maintenance activities and energy consumption during operational phase.

LCA is a quantitative approach that determines the impact of a product, technology or service under different impact categories based on life cycle inventories comprised of material and energy flows. However, LCA is not suited to identify all range of environmental, cultural or socio-economic benefits or trade-offs. It is imperative to consider not only the life cycle environmental impacts especially for emergency and response type of measures where environmental impacts cannot always be prioritized.

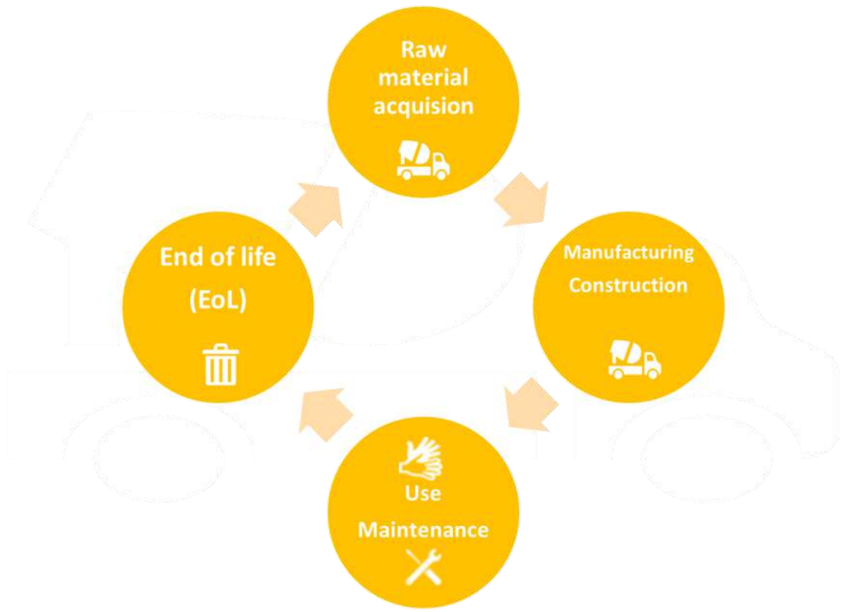


Figure 8 Life cycle stages covered

For this reason, in addition to relevant LCA hotspots, the non-LCA impacts are extracted from the characterization sheets. These impacts include

- Carbon sequestration/climate adaptation
- Air quality
- Biodiversity
- Flood protection and erosion control
- Urban space management and planning

Water management and quality

Soil quality and management

Fire prevention

Preservation of cultural heritage

Earthquake prevention

For the determination of hotspots, the characterisation sheets prepared for each solution is carefully studied and the following information was extracted to draw conclusions on environmental impacts and hotspots:

- Hazard – non-LCA impacts
- Primary and secondary function – LCA hotspots and non-LCA impacts
- Impact on cultural value – non-LCA impacts
- Maintenance – LC phase
- Recyclable and reusable – LCA hotspots (Recycling/circularity – avoided burdens)
- CO2 emissions – non-LCA impacts (Carbon sequestration/climate adaptation)
- Description – LCA hotspots particularly energy and material consumption including which type of materials consumed
- Material – type materials consumed
- Positive and negative aspects – LCA hotspots, non-LCA impacts and trade-offs
- Environmental and socio-economic co-benefits – non-LCA impacts

Color coding was used to represent the severity of the hotspot or level of benefit as below.

Severe hotspot		High-level benefit	
Significant hotspot		Significant benefit	
Moderate hotspot		Moderate benefit	
Minimal or potential hotspot		Minimal or potential benefit	

4.2 Implementation of the LCA methodology in the portfolio

LCA hotspots and non-LCA impacts for all the solutions studied under T3.4 is provided in Table 6 to Table 14

General conclusions for different solution types can be summarized as below:

- NBS
  - Many of the solutions create multi-benefits both from LCA and non-LCA aspects.
  - For the building-related solutions including green wall and green roofs, significant energy savings can be achieved. These savings can offset the climate impact created by the construction and maintenance of solutions including the impacts stemming from raw material consumption. The solution where high impact materials such as steel and plastics would pose a higher environmental footprint.
  - Parks and gardens and other urban green space solutions create many benefits in terms of climate adaptation, biodiversity, air pollution and soil quality. However, depending on the size, construction and maintenance of man-made green spaces would consume high impact construction materials, consume energy during construction and maintenance, require water for irrigation and generate waste during operation. Particularly, for large scale urban green spaces, composting of the pruning wastes should be considered.
  - For the erosion and flood control measures, main hotspots arise from the site preparation and maintenance operations. Especially, fuel consumption from the construction vehicles should be included in the life cycle inventories.
  - Whenever natural elements such as wood or logs are used, the release of biogenic carbon, at the EoL, within the biomass should be taken into account. If possible, reclaimed wood should be used to minimize impacts.
  - Although very difficult to estimate, the reduction in building energy demand for solutions lowering urban heat island effect and heat waves should be included in LCA.
- Circular economy solutions
  - All circular economy solutions presented in Table 7 present a focus on valorisation waste creating benefits two-fold. The first benefit is the prevention of waste that require landfilling or some other form of treatment. The second involves valorisation of waste as a secondary raw material for new products. In this way, both waste generation and primary raw material consumptions are avoided through CE solutions.
- Structural solutions
  - These solutions can be categorized into a couple of groups, where high impact or moderate impact construction materials are utilized to support buildings for protection from earthquakes and protect cultural heritage. Under this group, concrete and steel should be considered as high impact

materials. The level of effects created by manufacturing of these energy-intensive construction materials would depend on the amount used within the solutions.
    - When timer is used for structural solutions, biogenic carbon release at EoL should be factored in.
    - Although plastic and resins may also have high environmental footprint, if the amount consumed is low, associated life cycle impacts may not be pronounced.
    - Solutions like elevating building on piles require extensive construction leading to fuel and material consumption.
- Vernacular solutions
    - They are observed to cause fewer impacts as a result of material consumption.
    - Some architectural solutions and solutions like sun screens can create cooling effects. Therefore, it is important to include this aspect in LCA studies as accurately as possible.
- Flood specific solutions
    - Although some solutions are reusable and permanent, meaning long life time, extensive construction (such as seawalls) or high impact material solutions (such as urban floodwalls and barriers) may lead to high level of environmental effects.
    - If solutions like dams or debris basin, construction can elevate the environmental impacts significantly. Furthermore, maintenance may be necessary to drain the basins or dams. Opportunities for water reclamation should be sought to lessen the impacts.
    - Non-reusable solutions would end up creating waste to be handled after the flood.
- Earthquake specific solutions
    - Main concern is the construction materials used to earthquake-proof the buildings. If high impact materials such as concrete and steel are used, the LCA will result in high impacts.
    - The level of construction needed should be investigated especially when expansion of foundation system is applied.
- Wildfire specific solutions
    - Usually for these solutions, material consumption may lead to only moderate impacts.
    - If application requires flights or machinery, these operations should be included in life cycle inventories.
    - A number of solutions including cleaning under high voltage lines, access paths, stream bank armoring, road decommissioning or culvert modification, construction and maintenance would create environmental impacts.
    - Controlled weed burning, although may be necessary in certain instances, would create high amounts of GHG emissions.
- Heat wave specific solutions

    - Most of these solutions aim to improve the building energy performance or create cooling effect, which help to avoid some environmental impacts due to the use of electricity for cooling.
    - The materials used for insulating the buildings may have varying degrees of environmental footprints. Apart from reducing energy consumption during heat waves, insulation may also help to lower fuel consumption for heating during winter time. This added benefit would depend on the climatic conditions at the site of application.
    - Air conditioning creates a high burden on the environment due to the use of electricity.

For the following solutions listed in the portfolio, LCA methodology is not fully compatible due to the fact that for these solutions either material/energy flow estimations are not possible (such as ICT solutions or training) or the solutions presented can lead to a group of activities which should be studied specifically (such as planning solutions).

- Flooding: Rapid Damage Assessment and IMMERSITE® relies on software solution and therefore, an LCA based assessment is not meaningful.
- Earthquake: EEWS: PRESTo
- Wildfire: Early Warning System: territory level, prohibition of stubble burning in fire risk condition, biomass management, public training, specific plans development, social resources
- Heat waves: Low tech traditional practices of thermal regulation
- NBS: Distribution of urban green spaces, planning tools for urban expansion
- CE: Planning tools to control urban expansion, circular economy in cities (Cradle to Cradle strategy)
- Vernacular solutions: Building layout and courtyards in traditional urban patterns

Table 6 LCA matrix for NBS

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Climber green wall							Significant **energy savings** in the buildings. Water consumption for **irrigation** where the amount depends on the plant species. **Pruning wastes** would arise, which might be composted leading to positive circularity effect. **Steel and wire mash** are necessary for construction that may lead to climate impacts during their manufacturing. Material demand for planter green walls is higher than climber green walls. Use of recycled materials would help to avoid such impacts. Furthermore, chemical consumption during maintenance. Use of **fertilizers** may create water pollution. Positive effects on **climate adaptation, biodiversity, air quality**.
Planter green wall							
Green wall system							
Vegetated pergola							Potential for reduction in energy demand in surrounding buildings due to **cooling effect**. The amount of water needed for **irrigation** depends on the size of the application. **Pruning wastes** would arise, which might be composted leading to positive circularity effect. The impacts related to the material consumption depends on the material consumed. If concrete or metal is used instead of wood higher impacts should be expected. Use of recycled materials would help to avoid such impacts. **Food production** in these pergolas can create additional avoided burdens. Positive effects on **climate adaptation, biodiversity, air quality**.
Intensive & semi- green roof							Both solutions lower the **energy consumption** in building, however need energy for operation. Reduction in **building energy demand** would offset the energy required for operation. These solutions can also **reclaim water** but would also require water for **irrigation**. Water demand can be offset by water reclaimed and would depend on the type plants used in the green roofs. Higher amount of higher environmental footprint raw materials are required for green roofs such as waterproof materials, geotextiles, plastics and bricks. If recycled materials are used, these impacts would be lowered. Furthermore, chemical consumption during maintenance. Use of **fertilizers** may create water pollution. **Pruning wastes** would arise, which might be composted leading to positive circularity effect. Further circularity effects can be obtained by **food production** in intensive and semi-intensive green roofs. Positive effects on **climate adaptation, biodiversity, air quality**.
Extensive green roof							

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Parks and gardens							Parks and gardens may lead to reduction in **energy consumption** in surrounding buildings due to **cooling effect**. However, they require energy for operation and maintenance. Depending on the size water and material consumption as well as waste can be significant. Chemical consumption and the risk of water contamination due to use of **fertilizers** should be considered. If recycled materials are used for this solution and pruning wastes are composted, circularity effects can be achieved. Significant benefits in terms of **carbon sequestration, air quality and biodiversity**. Also benefits in terms of **urban space management and soil quality**.
Urban network NBS (green parking lots, green stips, green tram tracks, non-paved streets, green waterfront)							Potential water consumption for **irrigation** especially for green waterfront. Potential **energy consumption** due to construction should be taken into consideration, depending on the scale of application. Waste generation from **pruning wastes** and replacement of **drainage elements**. If pruning wastes are composted, circularity effects can be obtained. Materials consumption (mainly plastics) for drainage, which may require maintenance. These may create climate impacts from manufacturing of materials. If reused materials are utilized these impacts can be lowered. Positive impacts due to **climate adaptation, air quality, biodiversity, urban space management and soil quality**.
Green waterfront							**Fuel consumption and waste generation** due to construction. Waste generation from maintenance (**pruning wastes** in particular) should be considered. If pruning wastes are composted, waste management can be avoided. Environmental impacts due to use of **waterproof materials, substrate and drainage elements** should be investigated. Benefits on **climate adaptation, biodiversity, flood/erosion protection, urban space management and water quality**.
Structural soil							Fuel consumption due to **construction** processes leading to climate impacts. **Irrigation** may be necessary resulting in water consumption. **Pruning wastes** may be generated. Resulting impacts can be offset by soil amelioration. Moderate impact raw materials (sub-grade material soil, organic matter/compost) are necessary. Use of inert construction and demolition wastes and potential for food production create **circularity** effects. Significant potential for **carbon sequestration and soil carbon storage.** Additional positive impacts in **biodiversity, flood/erosion protection, urban space management, soil quality management**.

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Vegetative erosion slope control							Fuel consumption from **construction** processes needed to be assessed particularly if the area of application large. In this case, also high construction waste generation. **Pruning wastes** will arise and composting may lower the environmental impacts associated with waste management and create circularity. Significant **material consumption** is necessary in the form of geocell matrix including anchoring, drainage materials, topsoil, fill soil, concrete. Positive impacts for **biodiversity, flood/erosion protection and urban space management.**
Green pavements							Green pavements can lead to reduction in energy consumption in surrounding buildings due to **cooling effect**. If **irrigation** is necessary, water consumption should be included in the inventory. Significant material consumption that entails **energy intensive construction materials** including concrete and drainage materials may occur during construction. This may create **climate impacts**. **Recycling of concrete lawn swabs** can lower impacts associated with material consumption. Benefits related **flood protection, urban space management and soil quality**.
Redesign water bodies (reopened streams, vegetation engineering systems for riverbanks erosion control, reprofiling riverbanks, remeandering rivers)							Considerable **energy consumption** during construction and water treatment during operation. Water may be required for **irrigation**, but this solution also presents an opportunity for **water reclamation**. Depending on type of solution, **construction and maintenance wastes** would arise. Rocks, wire mesh, steel bars, geotextile, erosion control fabric are necessary for construction and maintenance creating environmental impacts. In case of **food production**, avoided burdens can be created. Benefits include **biodiversity, flood/erosion protection, urban space management, soil quality and management as well as water management.**
Green area for water management (swales, raingardens)							Due to smaller scale energy consumption and waste generation related to construction would be lower than other larger scale solutions. Impacts associated with **consumption of raw materials** may rise of the perforated pipes made of plastic are used in high amounts. Other than pipes, natural materials with lower footprint are used. Potential for **water reclamation and food production**. Additional benefits are related to **biodiversity, flood protection, urban space management, soil and water quality.**

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Floodplain - floodable park							Extensive need for construction leading to **high fuel consumption**. To a lesser extent waste generation from construction is possible. The environmental impact of **water-proof materials** should be investigated. Fuel and material consumption due to **maintenance requirements** should be considered, especially for repeated flooding. Non-LCA benefits include **biodiversity, flood protection, water quality, urban scape management and soil quality**.
Natural ventilation							Potential environmental impacts only if the solution is supported by **fans** that may require materials and energy for operation. Mainly for **protection of cultural assets**.
Contour felled logs							Low impact material consumption due to use of **natural materials** (wood). The **biogenic carbon release** impact due to use of wood should be investigated. Furthermore, climate impacts may arise due to **fuel consumption** from the machinery placing logs. Solution creates **flood/erosion protection** and affects **soil quality**.
Straw wattles							Low impact due to use of **natural materials**. Potential for using **on-site reclaimed wood debris**, which may lower the impact further. Environmental benefits are protection from flood/erosion and soil quality management.
In-channel tree felling							Low impact due to potential use of **natural materials**. **Local and burned trees** can be used if wood is utilized. Supports **biodiversity, water and soil management**.
Firebreak							Requires **extensive construction** operations not only initial phase but also for maintenance. **Fuel consumption** leads to adverse climate impacts. Disruption of **biodiversity** should be monitored. Creates protection from **wildfires**.
Green urban furniture							In addition to natural elements, **PVC and metals** may be required for the structure adding to environmental impacts. **Water consumption** for maintaining the green furniture. Benefits include **air quality, biodiversity, climate adaptation, water quality and urban space management**.

Table 7 LCA matrix for circular economy solutions

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
PPI ashes and sludge used as backfilling material (MUDIPEL) in the construction of retaining walls' structure							These circular economy solutions have the benefit of **avoided burdens** through both prevention of waste generation and i.e., **diversion from landfills**) subsequent management and **avoided** consumption of **primary raw materials**. Materials are consumed for construction however; this level of consumption is lower than their non-CE counterparts.
Green Liquor Dregs properties for sealing layer							

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Valorisation of construction and demolition waste (C&DW): new Precast Concrete A construction method for modular housing LIFE ECOVIA - recycling for infrastructure construction Recycled materials for the manufacture of composite boards for the construction industry							Avoided raw materials - Use of PPI ashes and paper sludge as a backfilling material - Use of Green Liquor Dregs (GLD), from the paper industry for AMD - Valorisation of construction and demolition waste (C&DW) to new Precast Concrete and new modular housing - Use of cardboard packaging, rubber tires and mixed plastics for highway materials - Recycled materials for the manufacture of composite boards for the construction industry
Solar Windows							Solar windows lead to significant **energy savings** in buildings. **Glass and metallic components** may create adverse climate impacts during manufacturing. Whether the savings offset these impacts should be evaluated.
The City of Phoenix Clean Palm Program - Valorising a costly waste stream Preseco Oy – Sustainable renewable energy and material inputs							These solutions entail conversion of waste to products without need for construction, creating **circularity**. These solutions palm frond wastes and organic wastes are used for feed and for their bio-carbon content, respectively. City of Phoenix clean palm program has the benefit of avoiding **water consumption**.

Table 8 LCA matrix for solutions for structures

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Sloped steel props (contrast system) Contrast steel props Steel support system for openings Steel rib for arches Steel rib for vaulted structures Steel tie rods for arches External steel tie rods for masonry without crosspieces Internal steel tie rods for masonry without crosspieces							These solutions, at different scales, require use of **steel**, which is a high energy intensive raw material. The **climate impacts** created due to manufacturing of steel depends on the amount of material used for the solution on a case specific basis. In order to lower the environmental impacts, all **reuse and recycling** possibilities should be taken. Benefits include **prevention of earthquakes and preservation of cultural assets.**
Vertical timber and steel props Sloped timber props (base contrast and peg contrast systems)							These solutions mainly rely on use of **timber** instead of steel, which as a natural raw material have lower environmental footprint. However, **release of biogenic carbon** at the EoL phase should be considered. In order to

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Horizontal timber props (unloading and equal contrast systems) Timber support system for openings Timber rib for arches Timber rib for vaulted structures Breakaway walls Pile foundation reinforcement							lower the environmental impacts, all **reuse and recycling** possibilities should be taken. Benefits include **prevention of earthquakes and preservation of cultural assets**. Breakaway walls and pile foundation reinforcements provide **flood and erosion protection**.
Polyester hoop system for columns and pillars Polyester hoop system for building portions Resin injections							While **plastics and resins** are the raw materials for these solutions, which can be energy intensive, the amount utilized would determine the level of environmental impacts. In order to lower the environmental impacts, all **reuse and recycling** possibilities should be taken. Benefits include **prevention of earthquakes and preservation of cultural assets**.
Grouting Elevate building on piles							Use of concrete and/or steel creates diverse climate impacts at the manufacturing phase. Particularly, elevating building on piles result in considerable amount of construction and demolition wastes. However, it also provides addition protection from **floods and erosion**. Benefits include **prevention of earthquakes and preservation of cultural assets**.

Table 9 LCA matrix for vernacular solutions

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Load absorbing structural connections between structural elements Elevated traditional structures Foundation drainage methods in vernacular architecture Lightweight timber structures Reinforcement of non-engineered vernacular buildings							Moderate **consumption of raw materials**, usually natural materials. Only in reinforcement of non- engineered vernacular buildings high impact concrete is used. For this solution, climate impacts should be considered. Whenever timber or wood is used release of biogenic carbon should be taken into consideration. Any **waste generation** during application or maintenance should be factored in. Vernacular solution mainly helps to **prevent flood and erosion, preserve cultural assets and prevent effects of earthquakes**.
Shading and sun screens in vernacular architecture							This solution can result in a reduction of building energy demands in surrounding buildings due to **cooling effect**. **Waste generation** can occur during construction and maintenance of the system up to a certain extent. Shades and sun screens can combat with heat waves and can be considered as a **climate adaptation** solution.
Architectural form of vernacular buildings in hot climate zones							Although case specific LCA studies are necessary for buildings, this type of architecture can result in **decreased building energy demands** for cooling.
Timber Laced Masonry construction Laced bearing wall construction for citadels							**Timber and masonry**, which are natural materials are only relevant hotspots for this solution. Due to use of biomass, **biogenic carbon release** should be considered during LCA. Creates protection against **earthquakes**.

Table 10 LCA matrix for flood specific solutions

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Temporary flood protection systems: Sandbags (buildings)							Sandbags are **not reusable** and should entirely be disposed of at EoL.
Temporary flood protection systems: Container systems (districts)							System is **reusable** however, at EoL should be disposed of. At disposal, there is a **risk of contamination** which necessitate stricter end of life treatment
Temporary flood protection systems: shields and panels (building)							More **energy intensive raw materials** such as aluminum, metal frames and stainless steel is required. **Potential climate impact** due to material manufacturing.

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Temporary flood protection systems: Free-standing and frame barriers							
Installation of check systems and pumps (building) Installation of check systems and pumps (district)							**Potential climate impacts** due to manufacturing of metal and plastic parts in pumps. **Operation energy consumption** which is much higher or the district-wide systems. **Potential for contamination** with motor oils.
Early Warning System							Helps to **avoid waste** as a result of damage reduction.
Seawalls							Requires **significant construction** leading to fuel consumption. Use of **energy intensive construction materials** such as concrete and steel leading to adverse climate impacts. **Generation of waste** during construction and EoL.
Urban floodwalls and barriers							Although not as extensive as seawalls, urban floodwalls and barriers require **construction**, which consumes energy. Use of **energy intensive construction materials** (concrete, metal, glass etc.) leads to climate impacts. **Reusable** solution.
Shoreline structure							Although **energy intensive materials** such as concrete is used to a certain extent, does not require extensive construction like seawalls.
Debris Basin							Flood water collected in debris basin can be used for **fire control**.
Sand or gravel basement filling							Provides protection from floods and effective in **preservation of cultural assets.**
Permanent floodwalls and gates for openings							Manufacturing of **energy intensive raw materials** such as concrete or glass can create **adverse climate impacts**.
Surface protection for materials vulnerable to the washing-out effects							Provides protection from floods and effective in **preservation of cultural assets**. Manufacturing of **water-resistant polymers** can lead to **climate impacts.**

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Dikes or dams							Requires **extensive construction**, which leads to fuel consumption. Construction materials including concrete and timber as well as energy consumption during construction create **climate impacts**. **Water collected** can potentially be used. Potential impacts on **water flows and biodiversity** should be monitored.
Identification of adequate storage facilities for movable heritage							**Energy consumption for maintaining** necessary conditions for preservation, particularly for extended periods of time.
Floating basement							

Table 11 LCA matrix for earthquake specific solutions

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Kerbs Reinforced perforations made with steel bars Application of composite materials strips to vaults and arches Artificial diatons							Depending on the solution, may require high **energy intensive construction materials** such as concrete, cement, steel or composite materials. As a result, **adverse climate impacts** may occur. Provides **protection for both earthquakes and cultural assets**.
Jacketing through composite material strips Coccioforte vaults consolidation Steel hooping for columns, pillars and beams CAM hooping for columns, pillars and beams FRP hooping for columns, pillars and beams							Raw materials used in this group of solutions are either less energy intensive such as mortar or tiles or energy intensive materials (steel for steel and CAM hooping) are used in smaller amounts compared to other solutions. Leads to both **earthquake protection** as well as **preservation of cultural assets**.
Expansion of foundation system							Requires **significant construction** leading to fuel consumption. Use of **energy intensive construction materials** such as concrete and steel leading to adverse climate impacts. **Generation of waste** during construction.

Table 12 LCA matrix for storm specific solution

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Rapid installation panels shutter Aquadam							Although some polymeric materials and metals in addition to lower impact wood or woven fabric can be used, the **reusable and recyclable** nature of solutions lower the potential environmental impacts over the life time.
Storm detector Lightning rod							Although metals are used, the **reusable and recyclable** nature of solutions lower the potential environmental impacts over the life time.
Underground drain systems							Although metals are used, **long service life of solutions** lower the potential environmental impacts over the life time. Potential **waste generation** during laying down the pipes and debris collected in the drainage system.

Table 13 LCA matrix for wildfire specific solutions

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Checdam Wood mulches Reforestation							Low environmental impact due to use of **natural material**s. Checdam also provides **flood protection**.
Hydromulches							Requires **water and fuel consumption** during application. Use of organic fibres, tackifier, suspension agents in high amounts.
Polyacrylamide PAM as soil binder							Requires **fuel consumption** for application.
Silt fence							The environmental impact can increase if metal posts are used. Due to **high maintenance requirement**, material consumption continues during use phase. **Recycling potential** at EoL.
Grade stabilizer							Low impact solution due to use of **natural materials** such as stones, logs and plants. Any construction energy demands should be considered. Creates protection against both **flood/erosion and fires**.
Sodium bentonite-based coating							Low impact solution due to use of **natural materials**. **Water consumption** for binder should be quantified and included in LCI.
Fire hydrant							Although metals are used for the hydrants, **long service life** reduced overall environmental impacts.
Sprinkler							Metals and plastics are used for the sprinklers, however in low amounts.

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
							During operation significant **water consumption** may occur.
Cleaning under high voltage lines Design access paths							Requires **extensive construction** operations not only initial phase but also for maintenance. Fuel consumption leads to **adverse climate impacts**. Disruption of **biodiversity** should be monitored
Early warning system							
Stream Bank Armoring							Low environmental impact from material consumption perspective (**natural materials** used). Depending on the level of construction required, significant **fuel consumption** may occur.
Road decommissioning							Low environmental impact from material consumption perspective (**natural materials** used). Depending on the level of construction required, significant **fuel consumption** may occur.
Culvert Modification							Use of **energy intensive construction materials** (concrete) may lead to adverse climate impacts. **Fuel consumption** due to significant construction needs. Construction **wastes** may arise however, opportunities for soil (for instance for backfilling) should be explored.
Debris Rack and Deflectors Trail Stabilization							Use of low impact **natural materials**. However, use of virgin biomass may lead to **biogenic carbon release**. **Reuse potential** for used burned logs or surrounding material may lower impacts. Impact on **biodiversity** should be monitored.
Fire curtains							Impacts depend on the fire resistant material of choice.
Perimeter protection strips Property Maintenance							Depending on the extend of the application area significant **construction and debris generation** may occur. Environmental impacts may continue as a result of **maintenance**.
Controlled weed burning							**Release of biogenic carbon** is a significant issue associated with this solution.

Table 14 LCA matrix for heat waves specific solutions

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
External thermal insulation composite system (ETICS): synthetic organic insulation							At construction stage use of **EPS, XPS and polyurethane** type of materials may lead to **climate impacts** however, they may be offset by the reduction of building energy demands. Material consumption for **maintenance** should be taken into consideration. **Wastes** can be generated during construction and EoL. In case of polyurethane, **air quality** should be monitored.
Internal thermal insulation system: synthetic organic insulation							
Cavity wall insulation							
External thermal insulation composite system (ETICS): synthetic inorganic insulation							Reduction of **building energy demands** for all solutions. Many **various materials** can be used for these set of solutions. Life cycle inventories should be carefully studied as different materials may lead to different life cycle impacts. Therefore, type of materials will be decisive in LCA results. Material consumption for **maintenance** should be taken into consideration. **Wastes** can be generated during construction and EoL. The amount of waste would depend on the scale of construction.
Internal thermal insulation system: natural and mineral insulation							
Vacuum insulated panels (VIP). External application							
Vacuum insulated panels (VIP). Internal application							
Internal thermal insulation system: aerogel							
Phase Change Materials (PCM)							
External thermal insulation of roofs							
Internal thermal insulation of roofs							
Insulated glazing							
Solar control glass							
Vacuum Insulating Glass							
Passive smart glass							
Aerogel Insulating Glass							
Active smart glass: electrochromic glass							
Passive smart glass: Phase Change Material (PCM)							
Ventilated façade							
Cool coverings, roofs							Reduction in **building energy consumption**. No significant construction requirement or waste generation. Life cycle inventories should be carefully studied as **different materials** may lead to different life cycle impacts. Therefore, type of materials will be decisive in LCA results.
Solar protection film							
Shade elements for façades							
Heat pump systems: geothermal heat pumps							Heat pumps can bring significant **savings in energy** consumption. Impact originating from the use of metals and plastics can be lower if the service life of the systems are long.
Heat pump systems: air to air							

Solution	Energy	Water	Waste	Material	Recycling/ circularity	Non-LCA impacts	Notes
Air conditioning							Air conditioning on the long run consumes **high levels of electricity** and can lead to **significant GHG emissions** in the background. If the energy source is **renewable**, these impacts can be lowered.
Shade sails							Although to the lesser extent than the building specific solutions, cool pavements may lead to reduction in energy consumption due to **cooling effect**. Lower environmental impact from textile use and low impact set up. Use of metals should be taken into account if applicable.
Cool pavements							Although to the lesser extent than the building specific solutions, cool pavements may lead to reduction in energy consumption due to **cooling effect**. Depending on the area of application significant **construction** may be necessary leading to **climate impacts**. These impacts can be exacerbated by use of energy intensive raw materials of asphalt and concrete. Whether reduction in energy consumption offsets these impacts should studied over the life time of the project. The longer the service life of cool pavements, the higher the **possibility for offsetting**.

5 Solutions Cost-Benefit Analysis (CBA)

Cost-benefit analysis (CBA) is one of the essential instruments of economic analysis. It has a very simple but also wholly universal character. CBA is a helpful tool for a wide variety of problems and situations. Nevertheless, to provide valuable information, CBA must be adapted to the specific area of interest.

The primary purpose of the offered CBA methodology is to provide to any user a **universal and complex tool for evaluating any selected solution from the cost-benefit point of view**. That is why the team decided to implement the methodology into the excel tool with a user-friendly interface. On the other hand, general CBA analysis is usually not adapted for investments in cultural heritage. The presented CBA Tool has therefore following advantages:

- **intuitive** and well described in the user's manual
- **interactive and dynamic** in changing the inputs
- **transparent**
- **universal** for any combination of solution and Open Lab
- **adapted to the specifics** of the cultural heritage
- **variable** in its complexity
- **suitable for fast and easy dissemination** to any region or monument.

Besides, the CBA Tool will help the users with:

- the decision-making
- comparing the selected solutions' costs and benefits
- generating and saving the reports.

5.1 Description of the development of the CBA methodology

With the awareness of the set goals, firstly, the methodology was developed in the following steps:

1. **literature review** of the CBA analysis approaches and cultural heritage specifics
2. **defining** of the general CBA frame according to the literature review
3. **implementation** of the specifics into the general CBA frame
4. **defining and precision** of the groups of costs and benefits
5. **determination** of the logical connections between the separate items in CBA

5.1.1 Literature review

In cultural heritage protection, many specific problem areas need to be considered in multidisciplinary decision-making processes. The first aspect is the essentially incalculable value of protected objects or regions. Therefore, **it is challenging to determine the value that needs to be protected, and it is even more difficult to value it in monetary value**. Various multifactor models can be used for building valuation (e.g., Kee, 2019). Utilization efficiency can be assessed by advanced statistical modelling (Placek et al., 2016). The benefits to local tourism can also be evaluated by multidimensional models (Massimo et al., 2013). However, it is always necessary to take into account the possible adverse effects of the use of these areas and buildings, which can, in extreme cases, lead to overtourism (Milman, 2015). Evaluation of the cultural heritage losses is one of the main aims of task 6.6, and users will have at disposal the separate tool.

Some risks in specific areas are growing significantly (Balasbaneh et al., 2019). It is **essential to protect the civilian population, infrastructure and culturally important objects and areas**. However, the selection of an appropriate tool is limited by a number of uncertainties, costs and specific requirements. In recent years, the necessity to minimize environmental impact and environmental sustainability has been added (Mei et al., 2018; Nesticò et al., 2015). For civilian buildings, relatively robust models can be used in risk protection planning that considers the life cycle in terms of energy and mass flows (e.g., Kohler, Lützkendorf, 2002; Balasbaneh, 2019). For most environmentally friendly practices, both the total implementation costs and the impact on use costs (Buyle, 2013; Sajid, Bicer, 2021), the net present value of the project (Carter, Keeler, 2008) or environmental sustainability (Ottelé et al., 2011) are essential. However, their application may encounter local monument care requirements regarding the applicability of materials and specific solutions (Annibaldi et al., 2020). **Implementing some technical solutions affect the historical value of the object or area** (Annibaldi et al., 2020) or must be adapted to historic buildings' specifics (Rotilio et al., 2020). Some structures and sites are even so specific **that preserving the historical value and protecting the object or area must be developed special procedures** (Alkan, Yazicioglu, 2020).

Protecting monuments or areas from serious risks (or elimination of their consequences) is one of the most complex problems. It is, therefore, necessary to use multi-criteria decision-making models to decide on specific tools and their use (Arroyo et al., 2015; Campos- Guzmán et al., 2019). Often these decisions are made intuitively, without thorough analysis and transparent evidence (Arroyo et al., 2016). However, when decisions are made at the level of larger territorial units, it is possible to significantly reduce the overall cost of analysis and subsequent implementation (Zhang et al., 2015). In relevant studies, we most often encounter life cycle analysis (LCA) (e.g., Kohler, Lützkendorf, 2002), process hierarchy analysis (AHP) (e.g., Arroyo et al., 2015; Fiore et al., 2020) and especially cost-benefit analysis (CBA) (Arroyo et al., 2016; Boardman et al., 1994; Carter, 2008; Kpamma, 2017). A particular modification on a similar principle is the "Choosing by Advantages" approach (Arroyo, 2016b).

In terms of time anchoring, it is necessary to consider the time horizon in which the CBA is made. Especially in projects whose funding is linked to various budgets and grant titles, the estimated costs and benefits before implementation deviate significantly from the subsequent reality (Priemus et al., 2008; Bernardos et al., 2021). It should also be taken into account that the risks assessed and analyzed in the present analysis have different intensities, probabilities and even consequences depending on the target site. Therefore, the use of CBA is particularly suitable for the evaluation of medium- and long-term measures (Coelho et al., 2016).

Due to the wide range of risks and situations that local authorities face in protecting important monuments, it is necessary to bring a tool that will allow the user to select relevant (in the economic point of view) solutions for a given situation. The specific tool is therefore based primarily on general approaches in this area (e.g., Kpamma, 2017; Priemus et al., 2008; Belay et al., 2016). However, it takes into account decisions in the conditions of protection of monuments from risky phenomena.

5.1.2 Defining of the general CBA frame

The general CBA frame is based on the summarization of the costs and benefits of the selected solution:

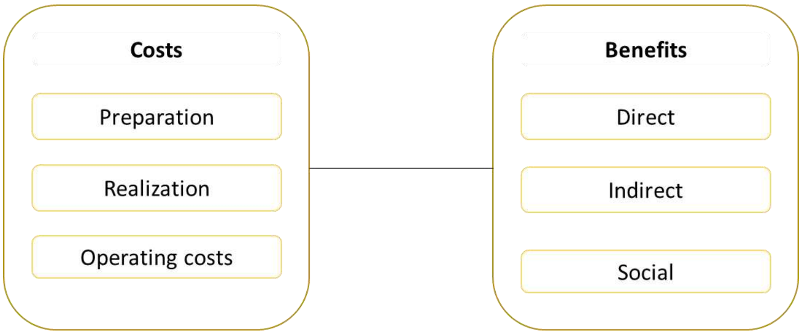


Figure 9 General frame of CBA

CBA is always assembled for an investment plan, solution, activity or another project. There are three categories of the costs connected to the project in general CBA:

- **preparation costs**
- **realization costs**
- **operating costs**.

Costs connected with the preparation phase of any project have to be incurred before the realization phase starts. These costs must be expended regardless of whether the project is finally realized or not. Realization costs encompass all the possible costs of the project implementation. Operating costs are linked with the post-realization phase of the project.

From the benefits point of view, we have to mention **direct benefits** connected with the project, **indirect benefits,** which are sometimes very hard to define and calculate and **social benefits** linked with invaluable assets.

As we can see in Figure 9, this scheme is too simple to provide enough information about the specific cultural heritage and solution impact. It does not contain the impacts on the current costs and benefits of the object, does not work with the lifespan of the solution, impact of the solution on the threat, frequency of the hazard and many other circumstances.

That is why we had to implement the specifics into this general frame and extend it significantly.

5.1.3 Implementation of the CH specifics

To make the general frame suitable for the specific solutions in CH protection, it is necessary to divide the processed information into three groups:

- **CH description**
- **hazard description**
- **solution description**

The **cultural heritage description** contains all the information about the current state in the CH object. These characteristics sum up the monument's value, current cost generated by the object and current benefits from the specific sources. Monument value is usually very difficult to calculate and can be determined from the insurance contracts, the previously needed investments or repair costs, or by the indirect methods. Very often, the cultural heritage value is not priceless. CBA Tool can, as an advantage, generate reports for the different values, and the user can compare the results for different situations.

The **hazard description** is a fundamental part of CBA. For the precise calculation of the solution impact, it is substantial to know the frequency and repercussions of the hazard. Both attributes influence the efficiency of the selected solution. Serious damage caused by very frequent hazard is the most appropriate situation for implementing some counter measure. On the other hand, implementing the solution against a rare hazard with small damage is usually ineffective because the costs are too high compared with the repair. Except for the damage itself, we have to mention the impact on CH objects costs and benefits.

The **solution description** must contain three dimensions of the costs mentioned in the previous chapter, but we have to add also the impact on the current costs and benefits of the OL. This impact can be positive or negative in both groups and is usually closely related to the solution itself, its extent, realization, the specific situation in the OL, season, market situation, local marketing and many other factors. Additionally, two characteristics influence the efficiency of the solution – lifespan and threat impact. Long-term solution breaks down the realization costs over a more extended period and covers more hazard incidents. It means that the whole impact of the solution is potentially more significant compared with the temporal or the short-term one. The threat impact expresses the efficiency of the solution against the hazard. Some of them eliminate the damage, and some reduce the damage partly.

While the OL description and the characteristics of the selected hazard are **static**, the description of the solution is **dynamic**. There are many possible solutions suitable for the OL and hazard combination chosen, but there are also many ways how to implement the selected solution. One solution can be realized in low-cost or high-tech variant; the cost can be different depending on the supplier/season/extend; different variants can have better or worse threat impact, etc. Therefore, the most important added value of the presented CBA Tool is fast and easy adding different solutions or their variants and comparing the results from the cost-benefits point of view. The users do not have to input repeatedly the data, which is the same for all the reports and can focus only on the best possible solution.

The extended frame of the CBA analysis is shown in Figure 10.

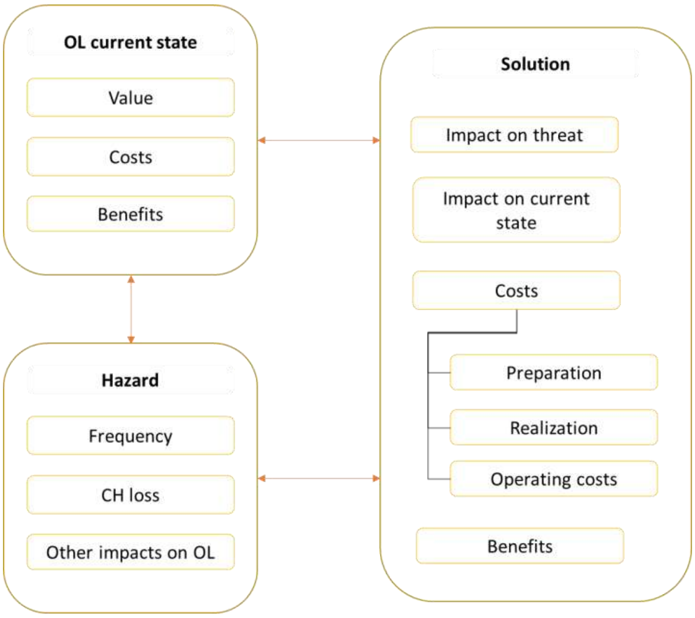


Figure 10 Extended frame of CBA (Authors)

5.1.3.1 Defining the groups of costs and benefits

Once the frame of CBA analysis is suitable for CH protection, we can move to the defining of the specific costs and benefits. All the costs and benefits are annual to make the CBA Tool as transparent as possible. In the CBA Tool, we work only with the costs and benefits, which can be influenced by the hazard or by the selected solution.

5.1.3.2 OL current state

As the OLs are specific, the sections of CBA must be universal enough for all of them. But not all of them must be present in each OL. The **benefits** are divided into the following groups:

- contributions from private sources
- contributions from public sources
- admittance fees
- revenues
- other

The **contributions from private sources** cover all the donations, sponsorships and partnerships with private donators. The **contributions from public sources** contain subsidies, grants, state support, grants from international organizations etc. It is important to differentiate those two sources because the volume of funds depends on the different factors. There are specific groups of preferred solutions connected, e.g., with the circular economy, energy savings, low carbon measures or climate favourable, which can (in addition to the function itself) increase the annual volume of the public sources. On the other hand, some solutions can be attractive for cooperation with the private sector.

The **admittance fees** are usually connected with tourism. Their amount depends on the area/monument/cultural heritage's attractivity, condition, additional services, weather, season, availability of the region etc. The main problem of the admittance fees is their variability. The hazard threat impact can reduce it to the minimum. On the other hand, some solutions can reduce the threat only at the cost of limiting tourist traffic.

Revenues are all the other incomes except the admittance fees. This group contains space rentals, sales of own products (e.g., souvenirs) etc.

Finally, we have to mention the **other** benefits. This section covers all the specific incomes, which are not suitable for the previous sections. But it can also contain indirect benefits if the user wants to count with them.

The costs are divided into the following groups:

- own production costs
- costs of goods and services
- energies
- personnel costs
- other

Own production costs mirror the revenues from the own products sold. Those two items are usually reported in the accounts, and production costs are always directly proportional to the revenues. **Costs of goods and services** (excluding energies) are paid to the external suppliers.

Energies are set aside because there are many solutions, which (among others) influence the energy consumption in the OL. Energy sustainability issues are also highly important for climate changes.

Personnel costs are one of the most important and sections with the highest share. They are reduced to the minimum when the OL is completely damaged. But they can also raise or lower following the implementation of the selected solution.

Other costs have a similar role to the other benefits. They cover all the specific costs, which are not mentioned in the previous sections. But they can also contain indirect costs if the user wants to count with them.

The share of each cost/benefits section will be various (it can also be zero) according to the character of the OL, its activities, operations, condition, market situation and many other factors.

5.1.3.3 Hazard and its impact

The user has to input the **hazard frequency** as one incident per number of year or month. Together with the **loss per one incident**, we can calculate the loss in the period of the solutions lifespan in the final report. While the lifespan and the effect of the solutions differ, we need a unified indicator of the hazard impact.

The user has two options to input the loss from one incident – by the absolute amount and percentage. Cumulation of the losses in time differs. While the amount is repeatedly deducted from the total value, the percentage reduces the previously calculated value after the hazard incident. The difference between both approaches and the result is shown in Figure 11.

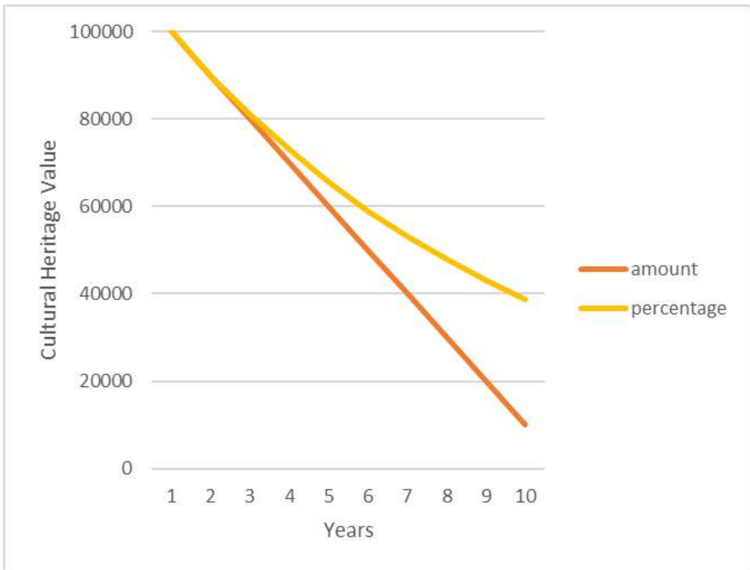


Figure 11 Difference between percentage and amount loss

Each hazard has a different **impact on the costs and benefits in the analysed part of OL**. The user is therefore wanted sked to add the costs and benefits after the incident. Although the common change is raising the costs and decreasing the benefits, this direction is not dogmatic. If the solution has only a partial effect, all the impacts of the hazard on costs and benefits in the object are proportionally reduced in the final CBA analysis. In this case, we are aware of a certain simplification, but it is in the interest of clarity and user-friendliness of the whole CBA Tool.

The last category of cost are **repairs, cleaning and other costs**. This section focuses on damage reparation. Here we have to say that sometimes it is impossible to return the CH to its original cultural/historical value. Still, there are costs connected to the re-operation of the monument or at least of what is left.

5.1.3.4 Solution

From the solution **lifespan** and its **impact on the threat**, together with the hazard frequency and impact, we can calculate the effect of the solution implementation. Each solution also impacts the current costs and benefits of the OL that were described above.

Furthermore, we have to calculate the specific costs and benefits of the solution. The benefits section is quite short because most benefits are directly connected with the costs and benefits of the OL. Nevertheless, there can be some specific indirect benefits, which should be calculated.

The costs of the solution have three sub-sections:

- preparation
- realisation
- operating costs

Preparation costs were divided into two parts. The first part contains summed up **external costs**, which are usually the part of the offered price for the preparation from the external supplier. The whole project can be priced completely, but there are typically separate sections for the preparation and realization. The second part develops the internal costs in detail into:

- preparation work
- training
- project documentation
- administration
- marketing
- other

The external supplier can deliver the turnkey solution. In this case, the internal preparation costs are marginal. Or the OL secures most activities in the **preparation phase**, and the external costs in this section are close to zero. The reality will be probably somewhere between those two extremes. Some solutions require the training of the staff before commissioning. Almost all solutions are connected with some kind of project documentation and administration. Especially the projects from EU funds also require marketing costs. Special needs of the OLs are included in other costs.

Realisation costs are, according to the same logic, split into external and internal costs. The external costs sum up the expenses paid to the external suppliers. Internal implementation costs represent the part of the project, which the OL itself realizes. Costs for training and others are similar to the preparation phase.

Preparation and realization costs are entered in the total amount. The CBA Tool calculates the annual costs according to the lifespan of the solution automatically.

Operating costs comprise the annual maintenance of the solution, the separate energy costs, administration and others. It is important to clarify that the solution can positively or negatively impact the current energy costs, but it can also generate the costs (or even earnings) in operation.

5.1.4 Determination of the logical connections

Figure 12 shows the logical connections between the inputs. The grey part of the solution contains specific costs and benefits of the solution which arise from the implementation.

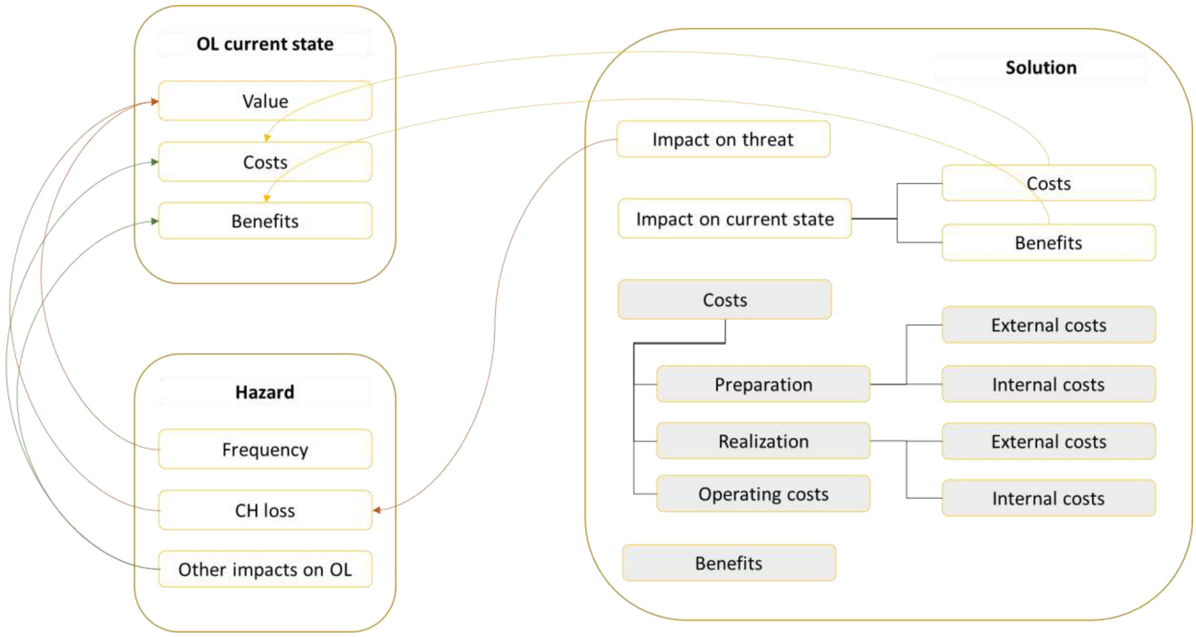


Figure 12 Logical connections

For the final CBA, it is essential to select the central philosophy of the analysis. We decided to use summarized cash flow as the most important calculating indicator. The results consider neither interest nor inflation rates.

The impact of the hazard depends on the frequency, damage and impact on the object costs and benefits. The solution can entirely or partially reduce the damage as well as the costs and benefits changes. This reduction is based on the suitability of the solution for the processed combination of hazard and object. The solution itself also influence the costs and benefits of the object.

CBA calculates and compares **three particular situations** – a current situation without any hazard and solution, a situation with hazard and without any solution and finally, a situation with a selected solution. Except for the whole sum of the costs, benefits, and damages (or reducing the damage), the CBA provides the user with the **benefit/cost ratio**. Based on this indicator, we can evaluate **cost-effectiveness**, especially between the hazardous situation with and without the solution. Basically, when the ratio rises, the solution is cost-effective; when it lowers, it is not. The increase of this indicator means that the overall solution benefits are higher than the costs incurred. The proportion of indicators before and after the implementation of the solution determines the solution effectiveness.

5.2 Implementation of the CBA methodology in the portfolio

The methodology is implemented into the interactive MS Excel tool. That is why the CBA tool's function is conditioned by the availability of a native MS Excel macro system based on VBA. The implementation will be described according to the sheets in the CBA tool.

When the user needs only basic CBA without any details and distinction of individual items, he/she can enter the sum into "Other", which is available in all cost/benefit groups, and leave the rest empty. This procedure is possible throughout the CBA tool. The user can refine the whole report by adding or dividing the separate items. Therefore, the tool is universal

5.2.1 Cultural Heritage

The user can define the CH object as the whole Open Lab. Still, CBA can also be generated for the dedicated area, building, monument or any other specified part of the OL. Thanks to this, the CBA tool can be quickly disseminated to many different regions and locations.

CULTURAL HERITAGE INFORMATION	
Name	*Basilica of San Vitale*
Location	*Ravenna, Italy*
Type	*Building*

CULTURAL HERITAGE VALUE	
Amount	*10 000 000 €*

CURRENT BENEFITS	*21 000 €*
Benefit	**Amount per year**
Contributions from private sources	*1 000 €*
Contributions from public sources	*3 000 €*
Admittance fees	*5 000 €*
Revenues	*2 000 €*
Other	*10 000 €*

CURRENT COSTS	*29 000 €*
Cost	**Amount per year**
Own production costs	*4 000 €*
Costs of goods and services	*2 000 €*
Energies	*2 000 €*
Personnel costs	*20 000 €*
Other	*1 000 €*

Figure 13 Cultural heritage information

5.2.2 Hazard

The definition of the hazard describes the specific parameters of the hazard in the Open Lab. Hazard probabilities and threats are usually well known or predicted in other Shelter

WPs. Generally, the CBA tool is determined for the group of selected hazards – heatwaves, flooding, earthquakes, subsidence, wildfires and storms. However, its design is universally applicable for almost any hazard damaging the cultural heritage with primarily material nature. The CBA tool has a high potential for use in new destinations or against newly recognized hazards. The portfolio of the solutions focuses mainly on the current risks, but with the onward climate change, we can expect new challenges.

HAZARD INFORMATION			
Type	*Storm*	**escription**	*Thunder and lightin*
Severity - description	*Heavy rain, hail, thunderbolt*		
The hazard occurs once every...		*1*	*years*
The effects of the threat are...		**Unique**	**Recurring**

Impact on cultural heritige value (fill one)	
Current cultural heritage value	10 000 000 €
Loss in currency	*- €*
Loss in percentage	*10%*

EFFECTS OF HAZARD

Benefits after implementation		*8 500 €*
Benefit	**Current**	**New amount**
Contributions from private sources	1 000 €	*500 €*
Contributions from public sources	3 000 €	*2 000 €*
Admittance fees	5 000 €	*4 000 €*
Revenues	2 000 €	*- €*
Other	10 000 €	*2 000 €*

Costs after implementation		*31 000 €*
Cost	**Current**	**New amount**
Own production costs	4 000 €	*3 000 €*
Costs of goods and services	2 000 €	*1 000 €*
Energies	2 000 €	*4 000 €*
Personnel costs	20 000 €	*22 000 €*
Other	1 000 €	*1 000 €*

Additional costs		*300 000 €*
Cost	**Description**	**Amount**
Repairs	...	*200 000 €*
Cleaning	...	*50 000 €*
Other	...	*50 000 €*

Figure 14 Hazard information

5.2.3 Filter

The user should have the whole solution portfolio imported into the CBA tool to select one of them and add relevant information. As the portfolio is the dynamic file and new solutions can be added in the future, there is a separate part in a CBA tool, which allows the user to update the solution's data. It is essential to keep in mind that all newly added sheets must fit the universal pattern and keep the primary layout of the sheet without any changes.

In the first step, the user can (but is not forced to) add any important characteristics and parameters. Or he/she can leave the selection module empty and choose the solution directly under the previous analysis or the results of decision making. The selection is shown in Figure 15.

The user can compare the basic characteristics of the solutions and prepare CBA for one or more suitable possibilities. We chose three **main characteristics**:

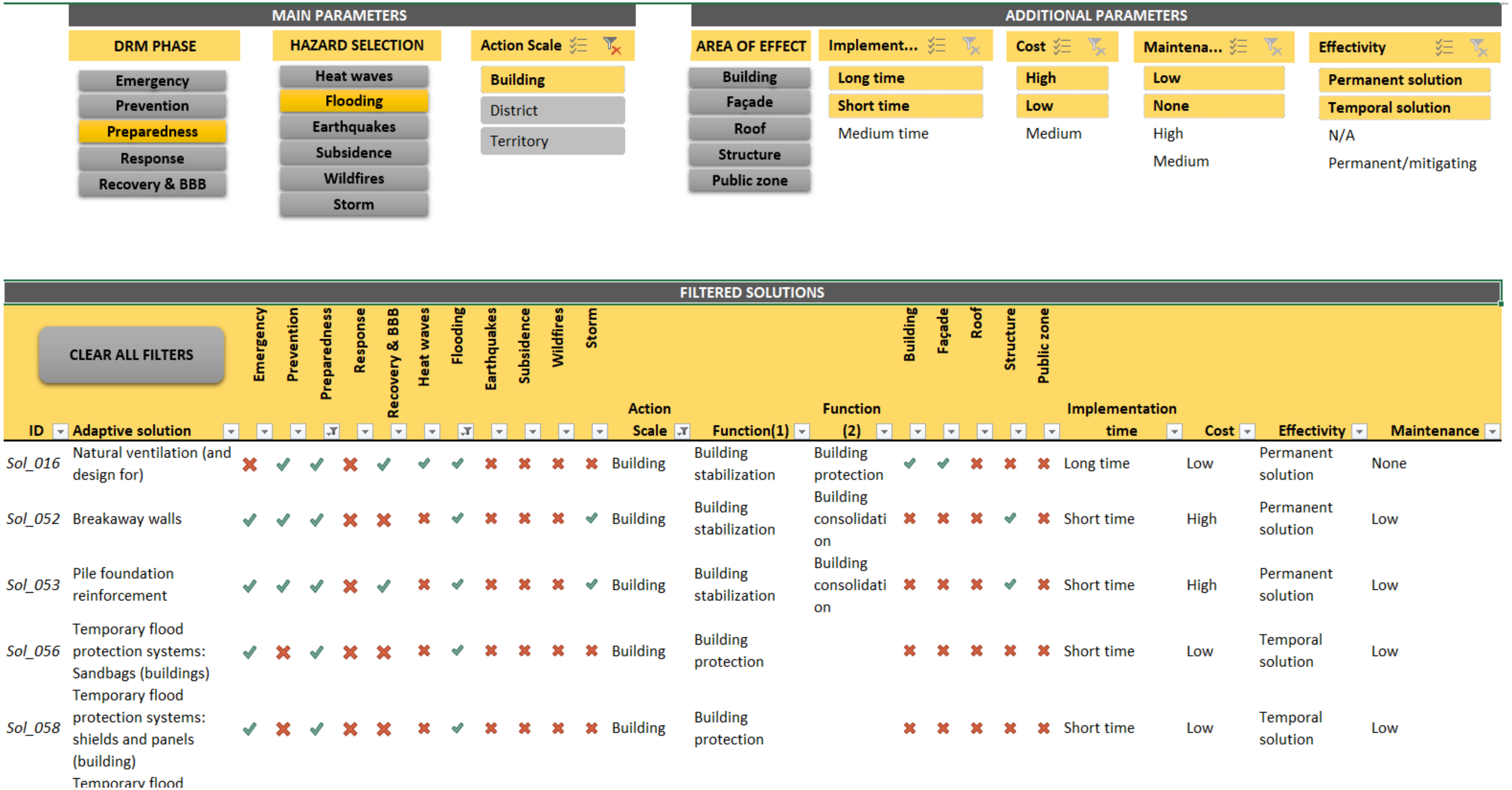
- DRM phase
- Hazard selection
- Action Scale

The multiple-choice selection filters the solutions, which meet all selected requirements together. CBA tool automatically filters and shows only solutions with the sum of selected characteristics and values.

The user can also filter the results according to the **additional parameters**:

- Area of effect
- Implementation time
- Cost
- Maintenance
- Effectivity

Once the solution is selected, the data automatically copy to the solution sheet, CBA sheet and the final report. If the user needs detailed info about the solution, it is available in the source file “Portfolio of solutions and strategies”.



ID	Adaptive solution	Emergency	Prevention	Preparedness	Response	Recovery & BBB	Heat waves	Flooding	Earthquakes	Subsidence	Wildfires	Storm	Action Scale	Function(1)	Function (2)	Building	Façade	Roof	Structure	Public zone	Implementation time	Cost	Effectivity	Maintenance
Sol_016	Natural ventilation (and design for)	✖	✔	✔	✖	✔	✔	✔	✖	✖	✖	✖	Building	Building stabilization	Building protection	✔	✔	✖	✖	✖	Long time	Low	Permanent solution	None
Sol_052	Breakaway walls	✔	✔	✔	✖	✖	✖	✔	✖	✖	✖	✔	Building	Building stabilization	Building consolidation	✖	✖	✖	✔	✖	Short time	High	Permanent solution	Low
Sol_053	Pile foundation reinforcement	✔	✔	✔	✖	✔	✖	✔	✖	✖	✖	✔	Building	Building stabilization	Building consolidation	✖	✖	✖	✔	✖	Short time	High	Permanent solution	Low
Sol_056	Temporary flood protection systems: Sandbags (buildings)	✔	✖	✔	✖	✖	✖	✔	✖	✖	✖	✖	Building	Building protection		✖	✖	✖	✖	✖	Short time	Low	Temporal solution	Low
Sol_058	Temporary flood protection systems: shields and panels (building)	✔	✖	✔	✖	✖	✖	✔	✖	✖	✖	✖	Building	Building protection		✖	✖	✖	✖	✖	Short time	Low	Temporal solution	Low
	Temporary flood																							

Figure 15 Selection of the solution

5.2.4 Solution

CBA report is based on the information about the solution impact on costs and benefits of the cultural heritage and a threat.

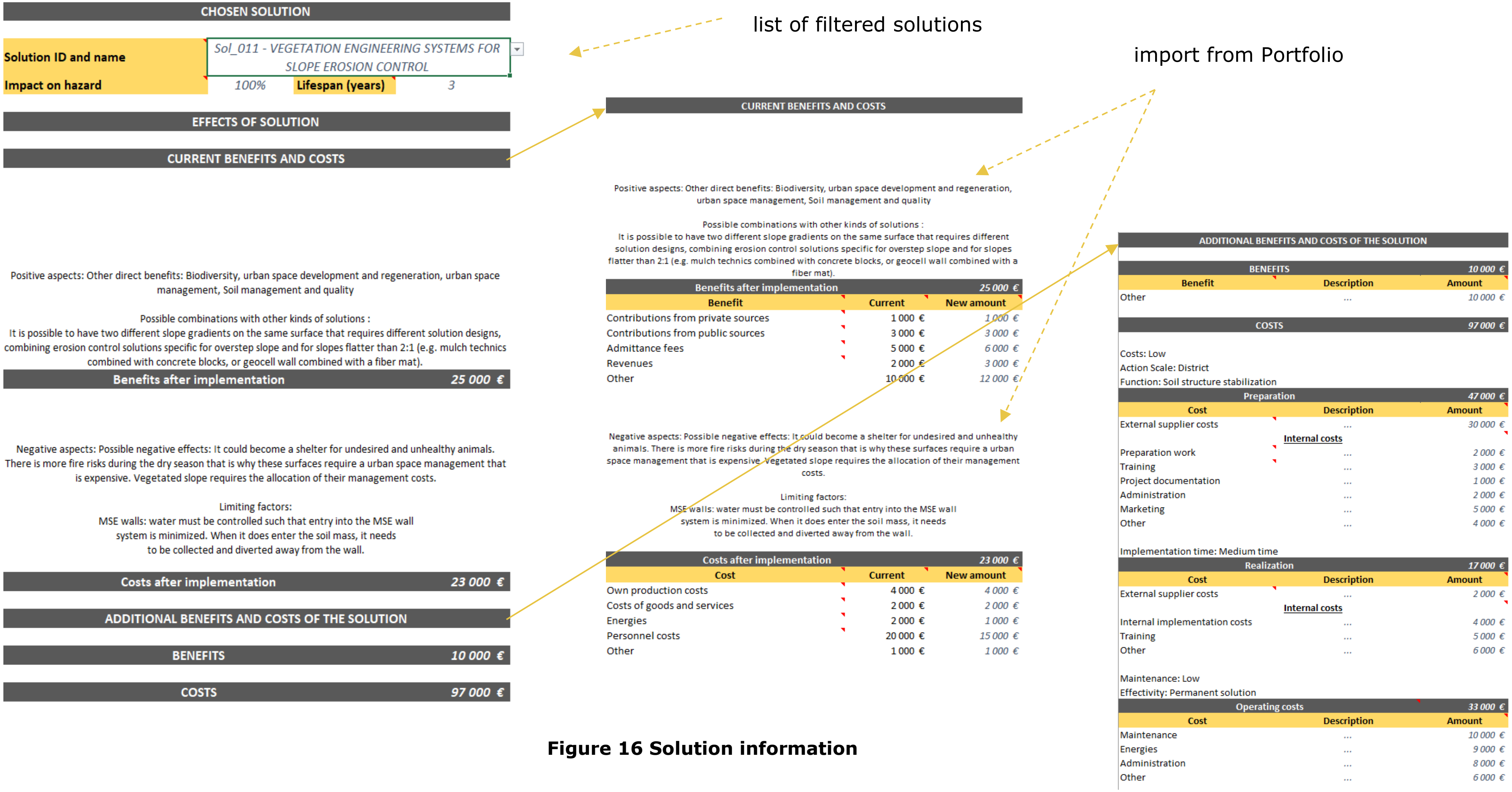
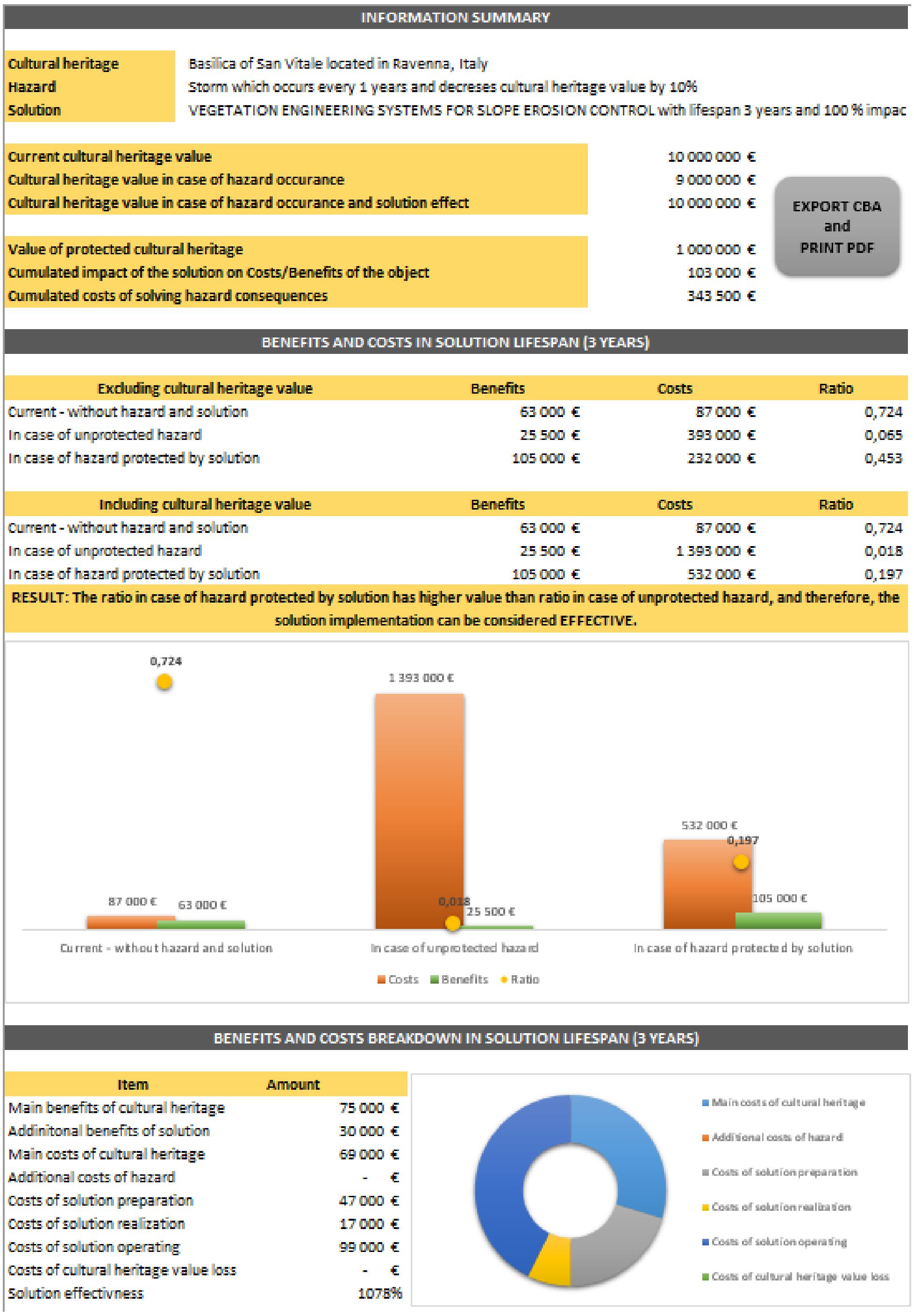


Figure 16 Solution information

5.2.5 CBA

CBA provides an economical part of project management and helps with the decision-making process from the cost-benefit point of view. It can compare the economic impact of different choices. On the other hand, it is limited to the areas quantifiable in money. Therefore, it must be integral but not the only part of solutions evaluation. The report is available as an interactive data sheet, which changes in real-time, but the button can export it to the separate static sheet. The user can add the solution to the Export sheet and compare different solutions and their main parameters.



INFORMATION SUMMARY

Cultural heritage	Basilica of San Vitale located in Ravenna, Italy
Hazard	Storm which occurs every 1 years and decreases cultural heritage value by 10%
Solution	VEGETATION ENGINEERING SYSTEMS FOR SLOPE EROSION CONTROL with lifespan 3 years and 100 % impac

Current cultural heritage value	10 000 000 €
Cultural heritage value in case of hazard occurance	9 000 000 €
Cultural heritage value in case of hazard occurance and solution effect	10 000 000 €
Value of protected cultural heritage	1 000 000 €
Cumulated impact of the solution on Costs/Benefits of the object	103 000 €
Cumulated costs of solving hazard consequences	343 500 €

EXPORT CBA and PRINT PDF

BENEFITS AND COSTS IN SOLUTION LIFESPAN (3 YEARS)

Excluding cultural heritage value	Benefits	Costs	Ratio
Current - without hazard and solution	63 000 €	87 000 €	0,724
In case of unprotected hazard	25 500 €	393 000 €	0,065
In case of hazard protected by solution	105 000 €	232 000 €	0,453

Including cultural heritage value	Benefits	Costs	Ratio
Current - without hazard and solution	63 000 €	87 000 €	0,724
In case of unprotected hazard	25 500 €	1 393 000 €	0,018
In case of hazard protected by solution	105 000 €	532 000 €	0,197

RESULT: The ratio in case of hazard protected by solution has higher value than ratio in case of unprotected hazard, and therefore, the solution implementation can be considered EFFECTIVE.

BENEFITS AND COSTS BREAKDOWN IN SOLUTION LIFESPAN (3 YEARS)

Item	Amount
Main benefits of cultural heritage	75 000 €
Addinitonal benefits of solution	30 000 €
Main costs of cultural heritage	69 000 €
Additional costs of hazard	- €
Costs of solution preparation	47 000 €
Costs of solution realization	17 000 €
Costs of solution operating	99 000 €
Costs of cultural heritage value loss	- €
Solution effectivness	1078%

Figure 17 CBA Report

6 Conclusions and next steps

The conducted work has allowed providing a Portfolio (Excel spreadsheet format) which gathers the solutions and strategies to lead Heritage owners/managers in their actions for climate adaptation. The methodology of implementation of the characterisation data-sheets has been conducted in a collaborative way and with a panel that includes experts, open labs and professionals. Every single characterisation sheet gathers details about the solution/strategy. These data allow the end-user to better understand the aims of the solution/strategy but also to better select the more suitable alternative for his or her situation.

Moreover, a Prioritization tool has been also developed by partners based on the core data of the portfolio and a set of criteria previously defined. Complementary, to the portfolio, to LCA and CBA methodology (See Solutions portfolio_LCA_CBA tool) have been developed in order to provide a deeper understanding of the suggested solutions or strategies to the end-users. The end-users have been a core indicator for the implementation of the simplified tool which provides a mix between the technical rigour and the usability of the portfolio.

Beyond this site-specific selection, a Decision Support System will be developed and will be fine-tuned into WP5 to lead the end-user to a pre-selection of relevant characterisation sheets.

All these actions allow to provide strong support to the manager and provide concrete solutions and strategies against climate hazard at different DRM phases and for the different typology of hazard. Integrated into the DSS, characterization sheets, prioritization tool, LCA, CBA tools will be part of an easily accessible dataset.

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8 Appendices

8.1 Appendix I- List of the prioritized solutions for any DRM phase

Adaptive solution	Hazard		DRM PHASES				PRIORITIZATION INDEX		
			Prevention	Preparedness	Response	Recovery & BBB	Territory scale	Urban scale	Asset scale
CLIMBER GREEN WALL	Heat waves		X		X				0.701
PLANTER GREEN WALL	Heat waves		X		X				0.642
Greenwall system	Heat waves		X		X				0.555
VEGETATED PERGOLA	Heat waves		X		X				0.728
INTENSIVE and SEMI-INTENSIVE GREEN ROOF	Heat waves	Flooding	X		X				0.457
EXTENSIVE GREEN ROOF	Heat waves	Flooding	X		X				0.606
PARKS AND GARDENS	Heat waves	Flooding	X		X		0.536	0.567	0.595
NBS STRUCTURES ASSOCIATED TO URBAN NETWORKS	Heat waves	Flooding	X		X		0.738	0.785	0.793
GREEN WATERFRONT	Heat waves	Flooding			X		0.383	0.399	0.430
STRUCTURAL SOIL	Flooding	Subsidence	X		X				0.700
VEGETATION ENGINEERING SYSTEMS FOR SLOPE EROSION CONTROL	Flooding		X		X		0.599	0.612	0.656
GREEN PAVEMENTS	Heat waves	Flooding	X		X				0.797
REDESIGN NATURAL AND SEMI-NATURAL WATER BODIES AND HYDROGRAPHIC NETWORK TO LIMIT FLOODS	Flooding		X		X		0.446	0.449	0.480
GREEN AREA FOR WATER MANAGEMENT	Flooding		X		X		0.632	0.637	0.636
FLOODPLAIN AND FLOODABLE PARK	Heat waves	Flooding	X		X		0.619	0.617	0.621
Natural ventilation (and design for)	Heat waves	Flooding	X	X		X			0.668
Straw wattles	Wildfires				X	X	0.704	0.690	0.697
In-channel Tree Felling	Wildfires	Flooding			X	X	0.705	0.701	0.700
Firebreak	Wildfires		X	X			0.164	0.171	0.211
Green urban furniture	Heat waves		X				0.801	0.799	0.800
Shading and sun screens in vernacular architecture	Heat waves			X		X			0.788
Timber Laced Masonry construction	Earthquakes		X	X		X			0.786

Adaptive solution	Hazard		DRM PHASES				PRIORITIZATION INDEX		
			Prevention	Preparedness	Response	Recovery & BBB	Territory scale	Urban scale	Asset scale
Building layout and courtyards in traditional urban patterns	Heat waves		X			X			0.764
Architectural form of vernacular buildings in hot climate zones	Heat waves		X			X			0.812
Load absorbing structural connections between structural elements	Earthquakes		X			X			0.812
Foundation drainage methods in vernacular architecture	Earthquakes	Flooding	X			X			0.841
Lightweight timber structures	Earthquakes	Storm	X			X			0.812
Laced bearing wall construction for citadels	Earthquakes		X	X	X	X			0.812
Reinforcement of non engineered vernacular buildings	Earthquakes		X	X	X	X			0.812
Breakaway walls	Storm	Flooding	X	X					0.423
Pile foundation reinforcement	Storm	Flooding	X	X		X			0.423
Load Paths	Storm		X						0.546
Elevate Building on Piles	Storm	Flooding	X			X	0.190	0.177	0.190
Seawalls	Flooding	Storm	X			X	0.270	0.248	0.266
Debris Basin	Flooding	Wildfires	X				0.208	0.228	0.220
Shoreline structure	Flooding	Storm	X			X	0.370	0.360	0.380
Sand or gravel basement filling	Flooding		X			X			0.631
Permanent floodwalls and gates for openings	Flooding		X			X			0.516
Surface protection for materials vulnerable to the washing-out effects	Flooding		X			X			0.621
Wet-floodproofing interventions	Flooding		X			X			0.447
Dikes or dams	Flooding	Storm	X			X	0.269	0.296	0.293
Urban floodwalls and barriers	Flooding		X			X	0.310	0.314	0.330
Identification of adequate storage facilities for movable heritage	Flooding		X	X					0.678
Floating basement	Flooding		X			X			0.368
IMMERSITE®	Flooding		X				0.532	0.524	0.535
Kerbs	Earthquakes					X			0.245
Reinforced perforations made with steel bars	Earthquakes					X			0.216
Application of composite materials strips to vaults and arches	Earthquakes					X			0.434
Artificial diatons	Earthquakes					X			0.368

Adaptive solution	Hazard		DRM PHASES				PRIORITIZATION INDEX		
			Prevention	Preparedness	Response	Recovery & BBB	Territory scale	Urban scale	Asset scale
Jacketing through composite material strips	Earthquakes					X			0.347
Coccioforte vaults consolidation	Earthquakes					X			0.359
Steel hooping for columns, pillars and beams	Earthquakes					X			0.540
CAM hooping for columns, pillars and beams	Earthquakes					X			0.540
FRP hooping for columns, pillars and beams	Earthquakes					X			0.340
Expansion of foundation system	Earthquakes					X			0.287
Storm detector	Storm		X	X			0.625	0.581	0.598
Lightning rod	Storm		X	X			0.785	0.756	0.774
Aquadam	Storm	Flooding	X	X			0.565	0.538	0.557
Underground drain system	Storm	Flooding		X		X	0.380	0.364	0.366
Checdam	Wildfires		X				0.765	0.758	0.763
Cleaning under high voltage lines	Wildfires			X			0.561	0.544	0.555
Design access paths	Wildfires			X			0.597	0.623	0.642
Early Warning System: territory level	Wildfires		X	X			0.955	0.961	0.953
Stream Bank Armoring	Wildfires				X		0.303	0.335	0.350
Road decommissioning	Wildfires				X	X	0.453	0.469	0.464
Debris Basin	Wildfires		X				0.208	0.228	0.220
Culvert Modification	Wildfires	Storm	X			X	0.406	0.369	0.391
Debris Rack and Deflectors	Wildfires				X		0.647	0.679	0.682
Trail Stabilization	Wildfires				X		0.586	0.614	0.592
Controlled weed burning	Wildfires		X				0.972	0.994	0.998
Reforestation	Wildfires					X	0.952	0.976	0.954
Prohibition of stubble burning in fire risk condition	Wildfires		X				1.000	1.000	1.000
Biomass management	Wildfires		X	X			0.843	0.873	0.846
External thermal insulation composite system (ETICS): synthetic organic insulation	Heat waves		X			X			0.458
External thermal insulation composite system (ETICS): synthetic inorganic insulation	Heat waves		X			X			0.458

Adaptive solution	Hazard	DRM PHASES				PRIORITIZATION INDEX		
		Prevention	Preparedness	Response	Recovery & BBB	Territory scale	Urban scale	Asset scale
Internal thermal insulation system: natural and mineral insulation	Heat waves	X			X			0.786
Internal thermal insulation system: synthetic organic insulation	Heat waves	X			X			0.786
Vacuum insulated panels (VIP). External application	Heat waves	X			X			0.643
Vacuum insulated panels (VIP). Internal application	Heat waves	X			X			0.765
Cavity wall insulation	Heat waves	X			X			0.676
Internal thermal insulation system: aerogel	Heat waves	X			X			0.716
Phase Change Materials (PCM)	Heat waves	X			X			0.716
External thermal insulation of roofs	Heat waves	X			X			0.614
Internal thermal insulation of roofs	Heat waves	X			X			0.777
Insulated glazing	Heat waves	X			X			0.645
Solar control glass	Heat waves	X			X			0.622
Vacuum Insulating Glass	Heat waves	X			X			0.624
Aerogel Insulating Glass	Heat waves	X			X			0.597
Solar protection film	Heat waves	X			X			0.791
Passive smart glass	Heat waves	X			X			0.594
Active smart glass: electrochromic glass	Heat waves	X			X			0.594
Passive smart glass: Phase Change Material (PCM)	Heat waves	X			X			0.594
Cool coverings	Heat waves	X						0.535
Cool Pavements	Heat waves	X			X	0.505	0.481	0.486
Ventilated façade	Heat waves	X			X			0.380
Shade sails	Heat waves	X				0.775	0.778	0.776
Shade elements for façades	Heat waves	X			X			0.825
Heat pump systems: geothermal heat pumps	Heat waves	X			X			0.541
Heat pump systems: air to air	Heat waves	X			X			0.463
Air conditioning	Heat waves	X			X			0.802
Cogeneration	Heat waves	X			X			0.408
Low tech traditional practices of thermal regulation	Heat waves	X			X			0.761

8.2 Appendix II- CBA Tool Manual

Version date: 20.05.2021

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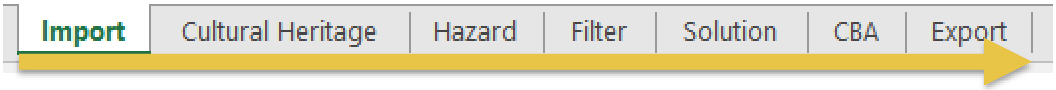
Important notes regarding the testing version (+ known issues)

- **The VBA** (macros for MS Office) **must be allowed**; it is an essential part of the design; if you are not familiar with VBA allowance, contact your IT support.
- The sheets and the workbook are protected by a password; no unsupported changes are allowed.
- The CBA Tool is available at the following link: CBA Tool

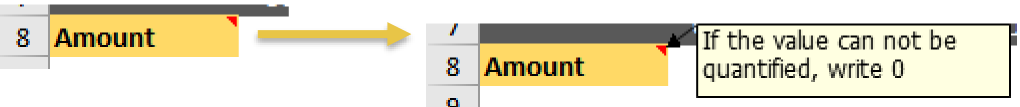
Overall logic of the tool

The use of the tool should be done in these basic steps:

1. Fill in data about the protected cultural heritage in sheet *Cultural Heritage*; these data should remain unchanged during the analysis of possible solutions
2. Fill in data about the hazard in sheet *Hazard* affecting the cultural heritage; these can be adjusted during the analysis of possible solutions
3. Use the sheet *Filter* to go through all the available solutions and find the ones used for the analysed problem
4. Select one analysed solution in sheet *Solution* and fill in its financial data
5. Check the CBA results on sheet *CBA*
6. Export CBA results for further use to sheet *Export*



If not sure about the items, use the red marking signalising an explanatory commentary.



All the financial data are calculated in euro. If you need to use a different currency, you can use the tool, just ignore the € unit.

9 Import function

If there is an updated version of the "Solutions and strategies" database workbook, you can import the actual data into the *CBA Tool.*

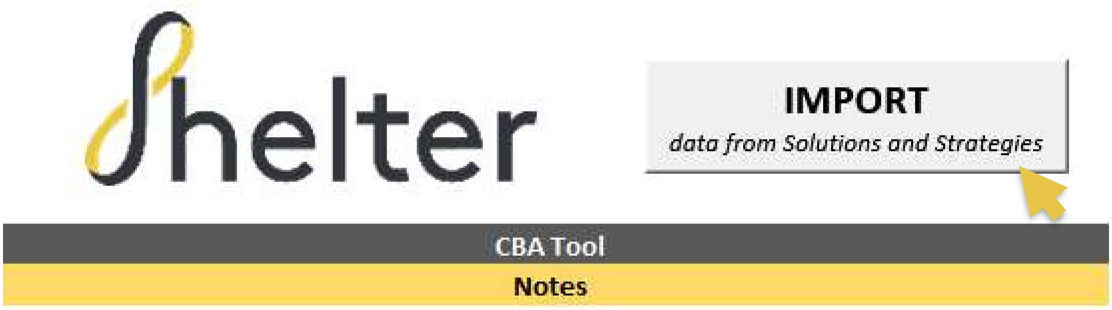
9.1 Import macro

Prepare the actual "Solutions and strategies" file and rename it to this exact name: "PORTFOLIO of solutions and strategies.xlsx".

Open the "Solutions and strategies" file, let it be opened.

Click on the *IMPORT* button and wait for a while (it can take even a few minutes depending on the speed of your device).

In case of any malfunction, you can still use the *CBA Tool* with obsolete data.



10 Cultural heritage information

Fill in data in the sheet *Cultural Heritage.*

10.1 Basic data

Fill in the basic information about analysed cultural heritage. This information is just qualitative and has no impact on calculations.

3	**Name**	*The main train station in Brno*
4	**Location**	*Nádražní, Brno, Czechia*
5	**Type**	*Building*

10.2 Financial data

Fill in the estimated financial value of the cultural heritage. If the value is unknown or cannot be assessed, write *0 €*.

7	CULTURAL HERITAGE VALUE	
8	**Amount**	*1 000 000 €*

Fill in the financial benefits resulting from the cultural heritage operation. If you miss the detailed items, write the summary in the field *Other*. Use the field *Other* if there are any benefits not fitting in the offered fields. You can use the sum in the header for data control. All the data are calculated per one fiscal year.

10	CURRENT BENEFITS	*21 000 €*
11	**Benefit**	**Amount per year**
12	Contributions from private sources	*1 000 €*
13	Contributions from public sources	*3 000 €*
14	Admittance fees	*5 000 €*
15	Revenues	*2 000 €*
16	Other	*10 000 €*

Fill in the financial costs resulting from the cultural heritage operation. If you miss the detailed items, write the summary in the field *Other*. Use the field *Other* if there are any costs not fitting in the offered fields. You can use the sum in the header for data control. All the data are calculated per one fiscal year.

18	CURRENT COSTS	*29 000 €*
19	**Cost**	**Amount per year**
20	Own production costs	*4 000 €*
21	Costs of goods and services	*2 000 €*
22	Energies	*2 000 €*
23	Personnel costs	*20 000 €*
24	Other	*1 000 €*

11 Hazard information

Fill in data in sheet *Hazard.*

11.1 Basic data

Select one of the basic hazard *Types* and use *Description* and *Severity – description* for any additional information and overview. These data are not used in any calculation.

Fill in the hazard occurrence. You can use the frequency in months or years. The point is to express how often does the hazard occur, resp. how many time does it affect the cultural heritage during the solution lifespan (see part 13.1). Choose if the hazard affects the cultural heritage just once (*Unique)* or repeatedly (*Recurring*). The *Unique* choice is used mainly in such cases if the hazard causes so many damages that the next affections are irrelevant, i.e. they bring no additional costs. The *Recurring* choice is used mainly in such cases when every other effect of the hazard brings additional damages and costs, which are cumulated with the previous ones.

3	Type	*Storm*	Description	*Heavy hailstorm*
4	Severity - description	*Damaged roof and facade, leakage in main hall*		
5	The hazard occurs once every...	*6*	*months*	
6	The effects of the threat are...	Unique	Recurring	

11.2 Financial data

Fill in the effect of the hazard on the cultural heritage. The point is to assess the financial extent of the damages done, and activities realised to eliminate the hazard consequences. These losses mean the irreversible reduction of the cultural heritage value. You can fill in the monetary amount or percentage of the cultural heritage value that is lost. Choose just one possibility; do not fill in both fields. The previously filled (0) cultural heritage value is displayed for your information.

8	Impact on cultural heritige value (fill one)	
9	Current cultural heritage value	1 000 000 €
10	Loss in currency	- €
11	Loss in percentage	*50%*

Fill in the effects of hazard occurrence on the cultural heritage benefits. The *Expected change* is the new annual value after the hazard strikes. The previously filled (0) cultural heritage benefits are displayed for your information. If there is no change, write the same amount as displayed in *Current.*

15	Benefits after implementation		*9 000 €*
16	**Benefit**	**Current**	**New amount**
17	Contributions from private sources	1 000 €	*1 000 €*
18	Contributions from public sources	3 000 €	*2 000 €*
19	Admittance fees	5 000 €	*4 000 €*
20	Revenues	2 000 €	*- €*
21	Other	10 000 €	*2 000 €*

Fill in the effects of hazard occurrence on the cultural heritage costs. The *Expected change* is the new annual value after the hazard strikes. The previously filled (0) cultural heritage costs are displayed for your information. If there is no change, write the same amount as shown in *Current.*

23	Costs after implementation		*37 000 €*
24	**Cost**	**Current**	**New amount**
25	Own production costs	4 000 €	*3 000 €*
26	Costs of goods and services	2 000 €	*1 000 €*
27	Energies	2 000 €	*10 000 €*
28	Personnel costs	20 000 €	*22 000 €*
29	Other	1 000 €	*1 000 €*

Fill in additional costs caused by the hazard occurrence. The *Amount* is one-off expenditure used to solve the damages caused by the hazard. If the hazard repeatedly occurs, fill in just the amount for one occurrence. Use the field *Description* for any information needed for your overview.

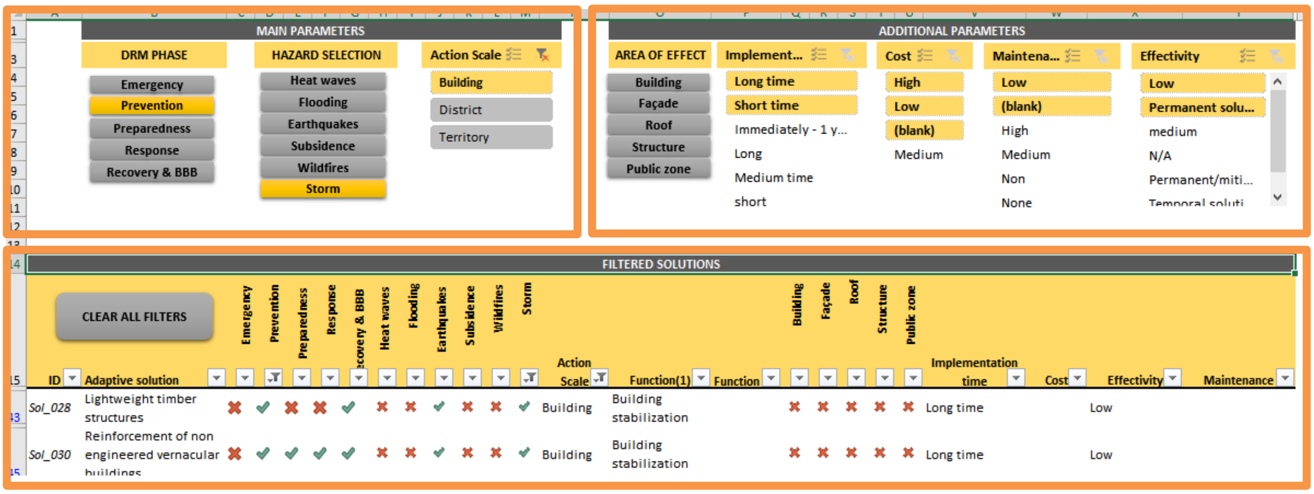
31	Additional costs		*300 000 €*
32	**Cost**	**Description**	**Amount**
33	Repairs	...	*200 000 €*
34	Cleaning	...	*50 000 €*
35	Other	...	*50 000 €*

12 Solutions filter

Use the sheet *Filter* to find all the possible solutions.

12.1 Basic logic

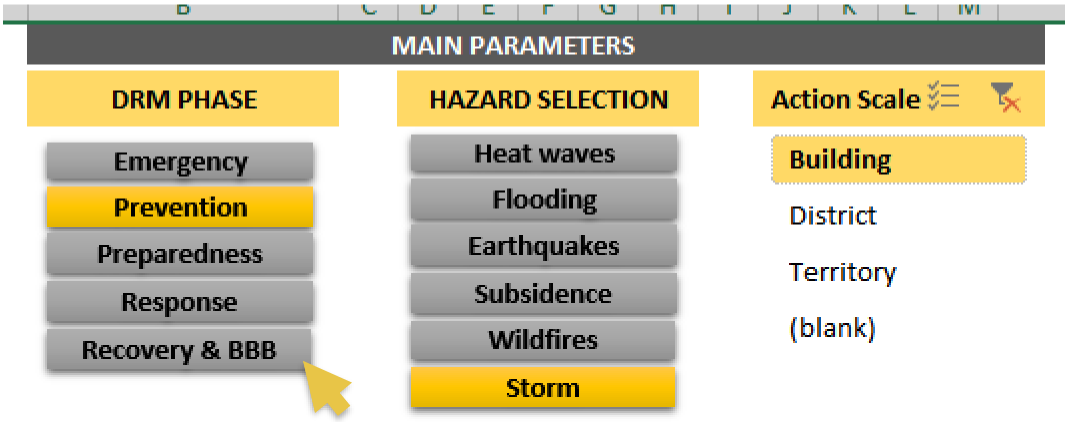
The sheet uses many filters to go through all the available solutions processed in the file "*Solutions and Strategies*". First, use the filters in section *Main parameters*, then use the filters in the section *Additional parameters* if necessary. The solutions meeting the specified criteria are shown in the lower part in *Filtered Solutions*.



Some filtering tools use on/off buttons, and some are multiple-choice slicers (MS Excel tool). They operate in a slightly different way. Already selected filters condition the slicers, i.e. they offer only available options.

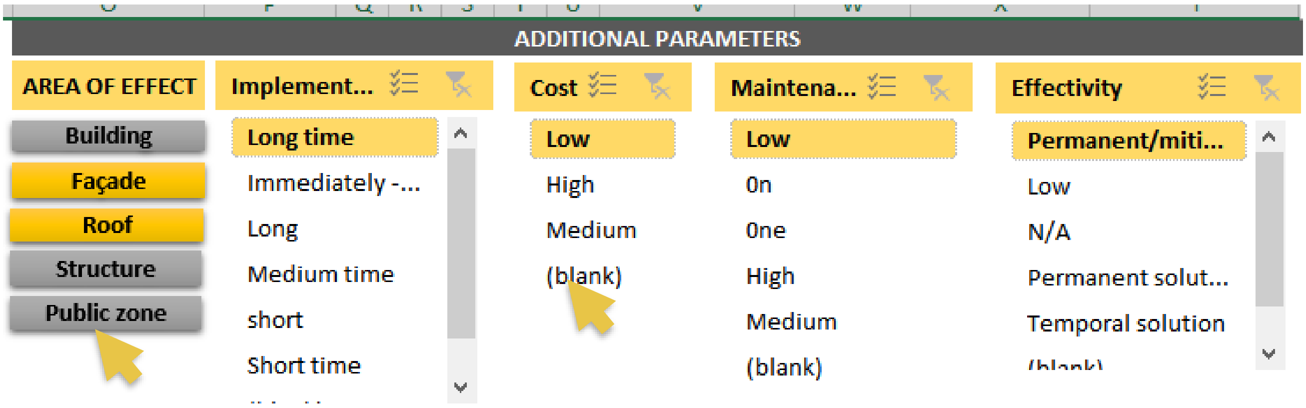
12.2 Main parameters

Use the main filters to choose the *DRM Phase*, *Hazard* and *Action Scale*. The *Hazard* filter is independent of the hazard filled previously in 0. All the filters use the logic *"and"*, which means that the solutions must meet all the filtered criteria simultaneously.



12.3 Additional parameters

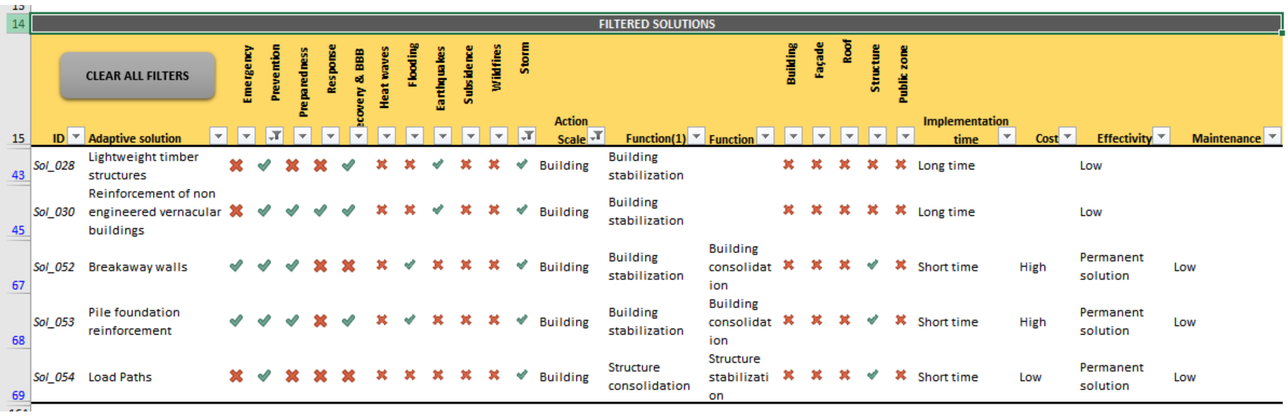
Use the additional filters to choose the solution *Area of effect*, *Implementation time*, *Cost, Maintenance and Effectivity*. The filters are based on the information from the source file *"Solutions and Strategies"* and are independent of the data filled in this tool. The choices in the slicers are dependent on the source data. All the filters use the logic *"and"*, which means that the solutions must meet all the filtered criteria simultaneously.



12.4 Filtered list

This table shows all the solutions meeting all the selected criteria. In some fields, the mark ✔ means that the solution meets these criteria, the mark ✖ means that the solution does not meet these criteria. The filtered solutions are here for your information, and one analysed solution is chosen in the next step 13.1.

The button *Clear all filters* allows you to put all the filters away at once.



FILTERED SOLUTIONS

CLEAR ALL FILTERS

	ID	Adaptive solution	Emergency	Prevention	Preparedness	Response	ecovery & BBB	Heat waves	Flooding	Earthquakes	Subsidence	Wildfires	Storm	Action Scale	Function(1)	Function	Building	Façade	Roof	Structure	Public zone	Implementation time	Cost	Effectivity	Maintenance
43	*Sol_028*	Lightweight timber structures	✖	✔	✖	✖	✔	✖	✖	✔	✖	✖	✔	Building	Building stabilization		✖	✖	✖	✖	✖	Long time		Low	
45	*Sol_030*	Reinforcement of non engineered vernacular buildings	✖	✔	✔	✔	✔	✖	✖	✔	✖	✖	✔	Building	Building stabilization		✖	✖	✖	✖	✖	Long time		Low	
67	*Sol_052*	Breakaway walls	✔	✔	✔	✖	✖	✖	✔	✖	✖	✖	✔	Building	Building stabilization	Building consolidat ion	✖	✖	✖	✔	✖	Short time	High	Permanent solution	Low
68	*Sol_053*	Pile foundation reinforcement	✔	✔	✔	✖	✔	✖	✔	✖	✖	✖	✔	Building	Building stabilization	Building consolidat ion	✖	✖	✖	✔	✖	Short time	High	Permanent solution	Low
69	*Sol_054*	Load Paths	✖	✔	✖	✖	✖	✖	✖	✖	✖	✖	✔	Building	Structure consolidation	Structure stabilizati on	✖	✖	✖	✔	✖	Short time	Low	Permanent solution	Low

13 Solution information

Fill in data in sheet *Solution.*

13.1 Basic data

First, choose one solution for further analysis using a drop-down list. The *Solution ID and name* are offered from the list of solutions filtered in step 0. If there are any filters set in the previous step, you will see all the existing solutions in the drop-down list.

Fill in the *Impact on hazard* of the solution. This expresses the degree of protection against damages caused by the hazard. If the solution negates the damages completely, write *100%. If* it does not protect against the hazard at all, white *0%.*

Fill in the *Lifespan* of the solution in years. This is the length of rational use of the solution, i.e. the number of years for which the solution protects against the hazard and its damages. The lifespan is assumed to be at least one year.

3	Solution ID and name	*Sol_084 - Expansion of foundation system*			
4					
5	Impact on hazard	*50%*	Lifespan (years)	*10*	

13.2 Financial data

Some of the solution data elaborated in the file *"Solutions and Strategies"* are shown here by the corresponding financial items. These shown data are not used in CBA calculation and serve only for better overview and clarity. Some of these data are not shown. They are missing in the source file.

11	Positive aspects: [1] FEMA. 2005.Hurricane Mitigation: A handbook for public facilities		
12	Benefits after implementation		*25 000 €*
13	Benefit	Current	New amount

Fill in the effects of solution implementation on the cultural heritage benefits. The *Expected change* is the new annual value after the solution is implemented and functioning. The previously filled (0) cultural heritage benefits are displayed for your information. If there is no change, write the same amount as displayed in *Current.*

11	Positive aspects: [1] FEMA. 2005.Hurricane Mitigation: A handbook for public facilities		
12	Benefits after implementation		*25 000 €*
13	Benefit	Current	New amount
14	Contributions from private sources	1 000 €	*1 000 €*
15	Contributions from public sources	3 000 €	*3 000 €*
16	Admittance fees	5 000 €	*6 000 €*
17	Revenues	2 000 €	*3 000 €*
18	Other	10 000 €	*12 000 €*

Fill in the effects of solution implementation on the cultural heritage costs. The *Expected change* is the new annual value after the solution is implemented and functioning. The previously filled (0) cultural heritage costs are displayed for your information. If there is no change, write the same amount as displayed in *Current.*

20	Negative aspects:		
21	**Costs after implementation**		***23 000 €***
22	**Cost**	**Current**	**New amount**
23	Own production costs	4 000 €	*4 000 €*
24	Costs of goods and services	2 000 €	*2 000 €*
25	Energies	2 000 €	*1 000 €*
26	Personnel costs	20 000 €	*15 000 €*
27	Other	1 000 €	*1 000 €*

Fill in the additional costs of solution implementation. This "project" is divided into three steps: *Preparation, Realization* and *Operating costs*. All these steps include only direct costs caused by the solution itself and cover the whole solution costs with no exception.

Fill in the possible solution benefits other than those mentioned above.

31	**BENEFITS**		***2 000 €***
32	**Benefit**	**Description**	**Amount**
33	Other	...	*2 000 €*

Fill in the *Preparation* phase that includes all the costs, which occur before the solution installation begins. *External supplier costs* include all the money, which are spent on external parties. *Internal costs* include money consumed by the organisation covering the analysed cultural heritage. All the costs are expressed as o one-time expense.

40	**Preparation**		***47 000 €***
41	**Cost**	**Description**	**Amount**
42	External supplier costs	...	*30 000 €*
43		**Internal costs**	
44	Preparation work	...	*2 000 €*
45	Training	...	*3 000 €*
46	Project documentation	...	*1 000 €*
47	Administration	...	*2 000 €*
48	Marketing	...	*5 000 €*
49	Other	...	*4 000 €*

Fill in the *Realisation* phase, which includes all the money spent on the solution installation. It covers mainly the solution price (value) included in *External supplier costs*. *Internal costs* include cash consumed by the organisation protecting the analysed cultural heritage. All the costs are expressed as o one-time expense.

52	Realization		15 000 €
53	Cost	Description	Amount
54	External supplier costs	...	2 000 €
55		Internal costs	
56	Internal implementation costs	...	4 000 €
57	Training	...	5 000 €
58	Other	...	6 000 €

Fill in the *Operating costs*. Be aware that this section represents the annual expenses on the solution service.

62	Operating costs		33 000 €
63	Cost	Description	Amount
64	Maintenance	...	10 000 €
65	Energies	...	9 000 €
66	Administration	...	8 000 €
67	Other	...	6 000 €

Now all the data are filled in.

14 CBA report

The sheet *CBA* includes all the calculated values and analysis outputs. There are no additional data inputs on this sheet. All eventual changes must be done on their respective sheets.

The general output summarises the information about the cultural heritage, hazard and solution. These are the main pieces of information for future orientation.

3	**Cultural heritage**	The main train station in Brno located in Nádražní, Brno, Czechia
4	**Hazard**	Storm which occurs every 6 months and decreses cultural heritage value by 5%
5	**Solution**	Pile foundation reinforcement with lifespan 10 years and 90 % impact on hazard

The next part includes the comparison of cultural heritage value loss and cumulated costs of scenario without and with the selected solution. All the amounts are calculated for the length of the solution lifespan.

The difference between *Cultural heritage value in case of hazard occurrence and solution effect* and *Cultural heritage value in case of hazard occurrence* represents the direct value conservation gained by the solution implementation, i.e. it is the field *Value of protected cultural heritage*. The difference between *Cultural heritage value in case of hazard occurrence* and *Cumulated impact of the solution on Cost/Benefits of the object* represents the saved (or increased) expenses caused by the solution implementation.

The button *Export CBA and PRINT PDF* is used for data print and export into the next sheet. See chapter 15.

7	Current cultural heritage value	1 000 000 €
8	Cultural heritage value in case of hazard occurance	358 486 €
9	Cultural heritage value in case of hazard occurance and solution effect	904 610 €
10		
11	Value of protected cultural heritage	546 125 €
12	Cumulated impact of the solution on Costs/Benefits of the object	274 000 €
13	Cumulated costs of solving hazard consequences	6 200 000 €

EXPORT CBA and PRINT PDF

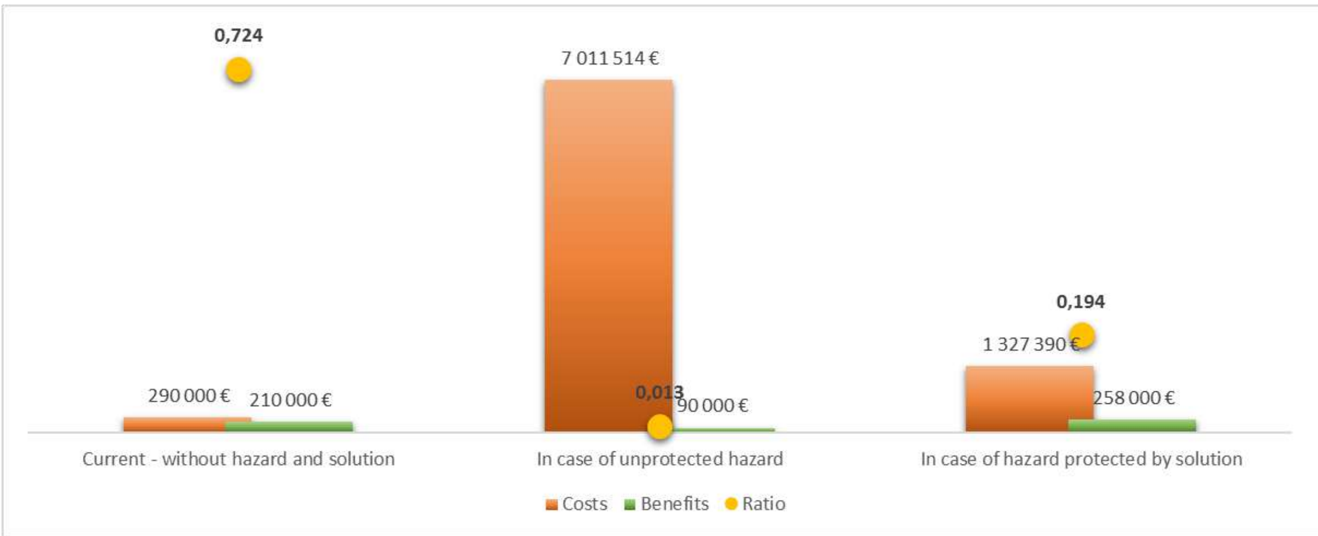
The next part of the output shows the cumulative sum of costs and benefits, *excluding* or *including* the changes in the cultural heritage value. The *Ratio* is calculated as the *Benefits/Costs* ratio. If the *Ratio In case of hazard protected by solution* increased compared to *Ratio In case of unprotected hazard*, the solution implementation could be considered effective.

17	Excluding cultural heritage value	Benefits	Costs	Ratio
18	Current - without hazard and solution	210 000 €	290 000 €	0,724
19	In case of unprotected hazard	90 000 €	6 370 000 €	0,014
20	In case of hazard protected by solution	338 000 €	1 230 000 €	0,275
21				
22	**Including cultural heritage value**	**Benefits**	**Costs**	**Ratio**
23	Current - without hazard and solution	210 000 €	290 000 €	0,724
24	In case of unprotected hazard	90 000 €	7 011 514 €	0,013
25	In case of hazard protected by solution	338 000 €	1 325 390 €	0,255

The overall evaluation of the calculation of the selected combination of the cultural value, hazard and solution is stated below. This is only a generalisation based on the change of the CBA ratio, no other aspects are included, and a complex approach should be used to assess further decision making.

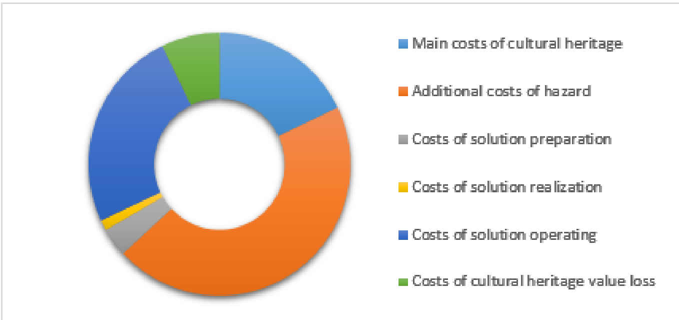
26	RESULT: The ratio in case of hazard protected by solution has higher value than ratio in case of unprotected hazard, and
27	therefore, the solution implementation can be considered EFFECTIVE.

The values "*Including cultural heritage value*" are displayed in the chart below. If the yellow dot (*Ratio*) is higher in the third column than in the second column, the solution implementation can be considered effective, but see 0.



The *Benefits and costs breakdown* summarises the cumulated sums of the most important partial items. It mainly displays the structure of expenses during the solution lifespan, which is also displayed in the chart on the right.

47	Item	Amount
48	Main benefits of cultural heritage	238 000 €
49	Addinitonal benefits of solution	20 000 €
50	Main costs of cultural heritage	238 000 €
51	Additional costs of hazard	600 000 €
52	Costs of solution preparation	47 000 €
53	Costs of solution realization	17 000 €
54	Costs of solution operating	330 000 €
55	Costs of cultural heritage value loss	95 390 €
56	Solution effectivness	1514%



15 Export

The button *Export CBA and PRINT PDF* on the sheet *CBA* (see 0) is used for two purposes: 1) A new .pdf file with the complete CBA is created, which allows modifying the inserted data and financial values without losing the complete analysis (see 15.1). 2) The main CBA data are stored in the *Export* sheet, where further comparison of different setting is possible (see 15.2).

15.1 The .pdf print

After the *export* button is clicked, a new *.pdf* file is to be printed. The file's name can be modified; the default folder is the same where the *CBA Tool* is located. The *.pdf* export can be cancelled in a standard way.

15.2 Export sheet

The export sheet consists of two main parts. The upper part contains all the information independent of the selected solution. The lower part contains the exported CBA results of each calculated solution. In such a way, a comparison of different solution effects is possible. All the data on the sheet are shown previously somewhere in the workbook – there is no new information here.

1	**CBA VARIANTS EXPORT**			
2				
3	**Cultural heritage**	The main train station in Brno located in Nádražní, Brno, Czechia		CLEAR EXPORT
4	**Hazard**	Storm which occurs every 6 months and decreses cultural heritage value by 5%		
5				
6	**Current cultural heritage value**		1 000 000 €	
7	**Cultural heritage value in case of hazard occurance**		358 486 €	
8				
9	**Including cultural heritage value**	**Benefits**	**Costs**	**Ratio**
10	Current - without hazard and solution	210 000 €	290 000 €	0,724
11	In case of unprotected hazard	90 000 €	7 011 514 €	0,013

13	Solution	Cultural heritage value in case of hazard occurance and solution effect	Value of protected cultural heritage	Cumulated impact of the solution on Costs/Benefits of the object	Cumulated costs of solving hazard consequences	Benefits Including cultural heritage value In case of hazard protected by solution	Costs Including cultural heritage value In case of hazard protected by solution	Ratio In case of hazard protected by solution
14	Pile foundation reinforcement with lifespan 10 years and 90 % impact on hazard	904 610 €	546 125 €	274 000 €	6 200 000 €	258 000 €	1 327 390 €	0,194
15	Pile foundation reinforcement with lifespan 10 years and 90 % impact on hazard	904 610 €	546 125 €	274 000 €	6 200 000 €	258 000 €	1 327 390 €	0,194

The *Clear export* button is used to clear the lower table with the solutions.

If there is a need to compare situations, which change the upper part of the *Export* sheet (for instance, the parameters of the hazard), it is necessary to work in a copy of the *CBA Tool* file.